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The geology, sedimentology, and stratigraphy of the Ordovician through Silurian Smith Formation, northern Seward Peninsula, Alaska

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THE GEOLOGY, SEDIMENTOLOGY, AND STRATIGRAPHY

OF THE

ORDOVICIAN THROUGH SILURIAN SMITH FORMATION,

NORTHERN SEWARD PENINSULA, ALASKA

A

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Timothy John Ryherd, B.S.

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Abstract

The purpose of this study is to determine the stratigraphic relationships and depositional settings of three outcrops at Cape Deceit, northern Seward Peninsula, Alaska. These rocks are lower Paleozoic limestone, dolostone, and shale. They have CAI values that indicate greenschist facies metamorphism. They have retained most of their primary sedimentary fabric, although they are juxtaposed with multiply deformed calc-silicate schists. The sedimentary rocks were deposited as a prograding base-of-slope apron. Environments recognized include distal basin, outer apron and inner apron. Ordovician graptolites and Ordovician through Silurian conodonts occur in these outcrops. Chronostratigraphic and environmental relationships suggest there is a genetic relationship between these three individual outcrops and that, when combined, they form a composite stratigraphic section named the Smith Formation. The Smith Formation is correlative in age with carbonate rocks of the York Mountains and western Brooks Range.

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1.0 Introduction

1.1 Objective

The purpose of this study was to describe, model the depositional setting, determine stratigraphic relationships, and estimate the mineral potential of three unique outcrops of early Paleozoic rocks west of the village of Deering, on the northern Seward Peninsula, Alaska (fig. 1). Exposures of the lower Paleozoic carbonates and shales occur primarily in sea cliffs at and near Cape Deceit (fig. 2). The three sections warrant investigation because they retain most of their internal sedimentary fabric, in contrast to the surrounding intensely deformed metamorphic rocks which have schistose fabrics with only hints of primary fabric.

The Deceit Formation (Ryherd and Paris, 1987) is the lithostratigraphic name originally applied to the rock units described in this study. This name is changed here from the Deceit Formation to the Smith Formation to avoid potential problems with nomenclature established by Guthrie and Matthews (1971). A detailed discussion may be found in section 2.0.

This study begins with detailed descriptions of the primary sedimentary characteristics of the undeformed Smith Formation. Primary sedimentary features are the basis for interpretation of the general depositional framework. Chronostratigraphic data

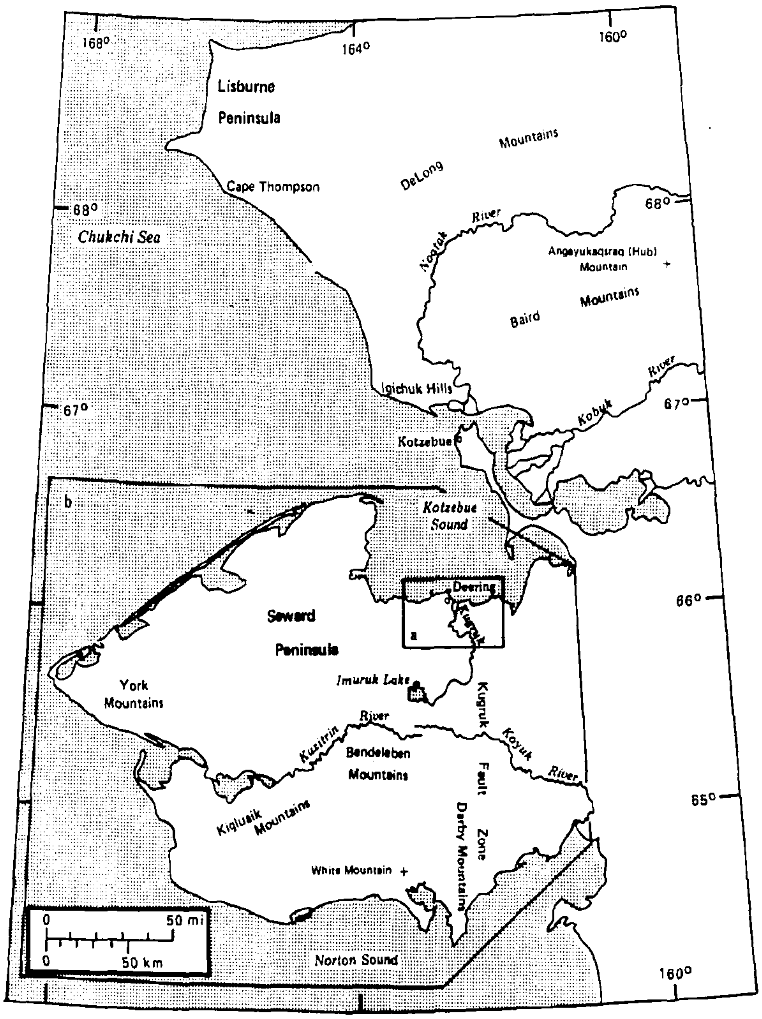

Figure 1. Location map of the Seward Peninsula and western Brooks Range. Outline a indicates area covered in Figure 2. Outline b indicates area covered in Figure 3.

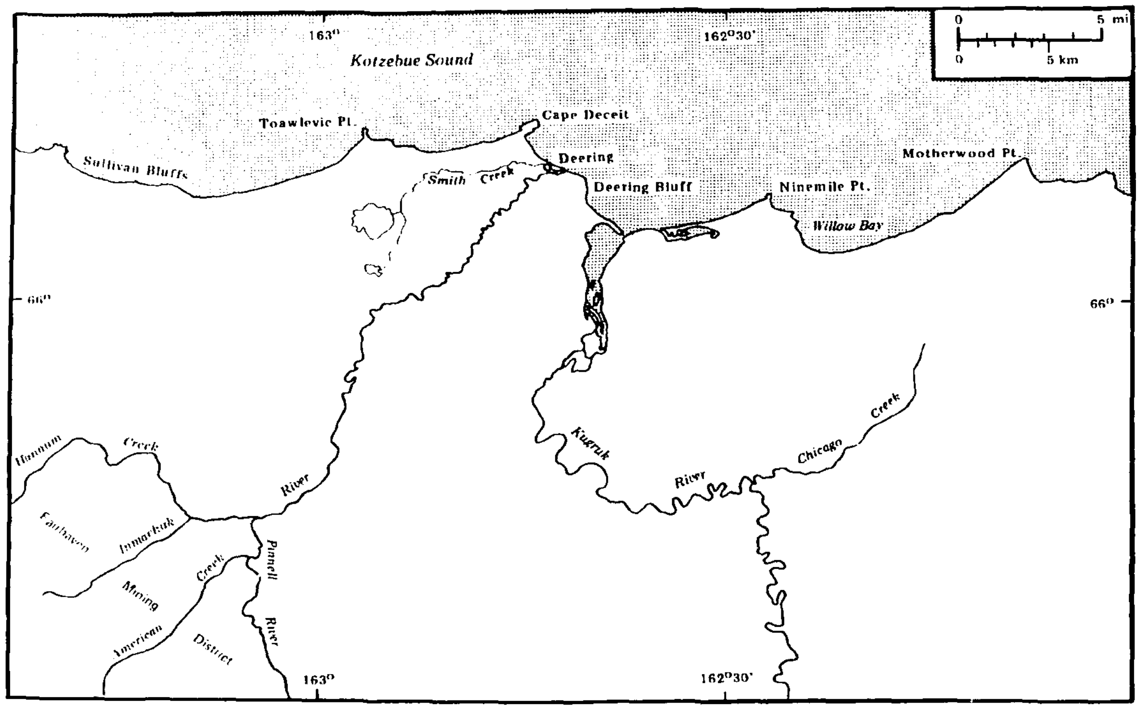

Figure 2. Location map of the Deering, Alaska area from Sullivan Bluffs to Motherwood Point.

presented here includes the description of a suite of graptolites discovered in the field area during this study. The stratigraphic relationships of the different exposures is incompletely understood. However, by integrating chronostratigraphic and lithologic data I offer a possible stratigraphic sequence for the Smith Formation. This new stratigraphy allows a better understanding of the regional relationships of the Smith Formation.

1.2 Geographic Setting

Physiographically, the Seward Peninsula is underlain by open rolling tundra with spruce forest confined to the southeastern part of the Peninsula. Cottonwood trees, alder and willow shrubs grow in favorable locations farther north and west (Hopkins, 1963). Mountain ranges of the Seward Peninsula include the Darby, Bendeleben and Kigluaik Mountains in a discontinuous arc in the south, and the York Mountains on the western tip. The Imuruk Lake lava plateau and the Kuzitrin River Basin separate the field area from the Bendeleben Mountains. Recent sedimentary deposits characterize the northwest coast and form an extensive low-lying coastal plain.

The Darby Mountains of the southeast Seward Peninsula trend north from Norton Sound for about 75 km (fig. 1). The Bendeleben Mountains form an arc westward 80 km from the north end of the

Darby Mountains. The Kigluaik Mountains arise about 20 km from the east end of the Bendeleben Mountains and continue southwestward to within 15 km the Bering Sea. High grade metamorphic rocks and/or granitic batholiths make up the cores of all three mountain ranges with low-grade metamorphic rocks surrounding them (fig. 3). The York Mountains, located on the western Seward Peninsula, are about 100 km west of the other three mountain ranges. The York Mountains are less rugged in relief than the Kigluaik, Bendeleben and Darby Mountain ranges. The York Mountains also differ in composition from rocks of the other ranges, comprising weakly metamorphosed to unmetamorphosed sediments as opposed to the metamorphic rocks of the Kigluaik, Bendeleben and Darby Mountains.

The Imuruk Lake lava plateau is an area of gently undulating hills and lowlands surrounding Imuruk Lake south of the field area. The plateau covers an area of approximately 3000 km^2 and includes several Quaternary and Tertiary basaltic lava flows and volcanic vent features. The most extensive flows of the Imuruk Lake lava plateau extend from Kotzebue Sound on the north to the Kuzitrin River on the south. The youngest lava flows have a fresh, unaltered appearance.

The setting for this study is a group of isolated coastal outcrops on Kotzebue Sound approximately 75 km south of Kotzebue,

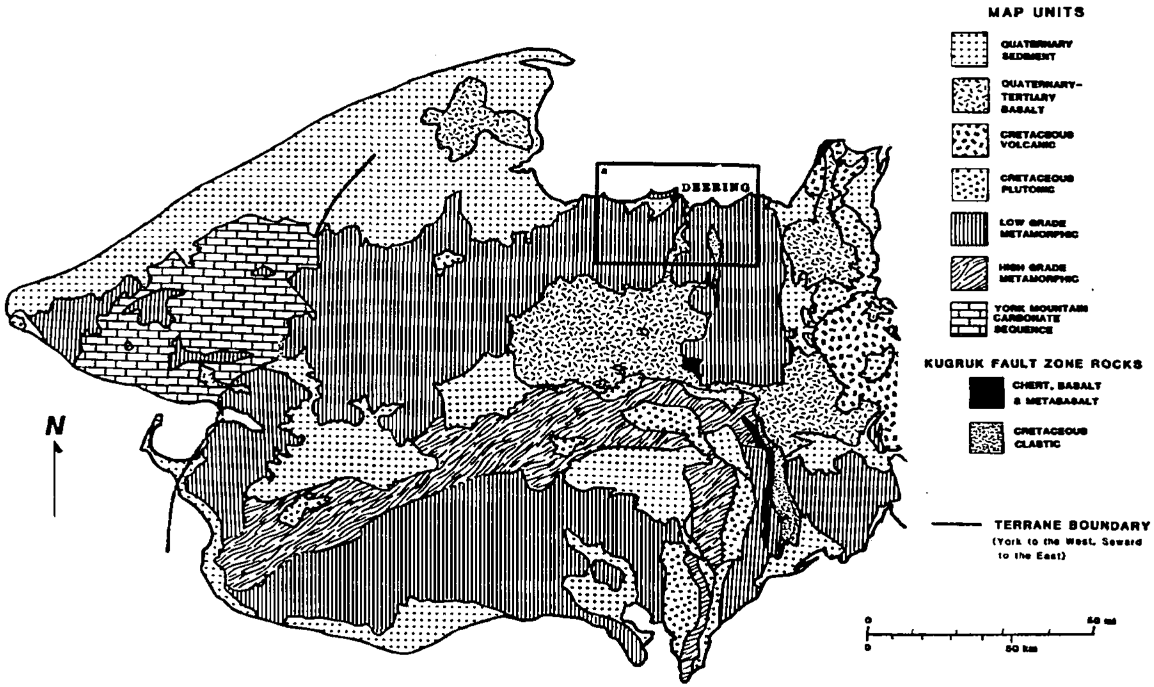

Figure 3. Generalized geologic map of the Seward Peninsula (modified after Hudson, 1977)

Alaska, and 2 km west of Deering, Alaska (fig. 1). The area covered includes portions of the Kotzebue A-1, A-2, and A-3 quadrangles. The study area lies approximately at Lat. $66^{o}05'$ N., Long. $162^{o}45'$ W.

1.3 Previous Work

1.3.1 Regional Studies

Geologic exploration of the Seward Peninsula essentially began with the discovery of gold in the early 1900's. Brooks and others (1901) conducted a reconnaissance study of the Nome area and Collier (1902) did the same in the northwestern Seward Peninsula. Knopf (1908) studied the geology of the tin deposits on the western Seward Peninsula in and around the York Mountains. Smith (1910) mapped part of the Solomon quadrangle, and Moffit (1913) mapped part of the Nome quadrangle.

More recently, Sainsbury (1969a, 1969b, 1972, and 1974) mapped the Teller and Bendeleben quadrangles, and Miller and others (1972) mapped the eastern Solomon and southeastern Bendeleben quadrangles. Hudson (1977) and Robinson and Stevens (1984) compiled geologic maps of the entire Seward Peninsula, and Till and others (1986) mapped and compiled fossil data for the Solomon, Bendeleben and southern Kotzebue quadrangles.

Other topical studies on the Seward Peninsula have concentrated on more specific geologic problems. Hopkins (1963) studied the geology of the Imuruk Lake area and Hopkins (1967) discussed the surficial geology of the entire Seward Peninsula and surrounding region. Kaufman and Hopkins (1986) described the glacial history of the Seward Peninsula. Intrusive rocks of the Seward Peninsula were studied by Miller (1972), Miller and Bunker (1976), Hudson (1979), and Hudson and Arth (1983). The metamorphic rocks of the Seward Peninsula were studied by Sainsbury and others (1970), Till (1982, 1984), Till and others (1983), Forbes and others (1984) and Armstrong and others (1986). Gardner and Hudson (1984) and B.E. Patrick (unpublished manuscript) addressed the structural history of the Seward Peninsula. Aspects of the regional mineral potential were discussed in Sainsbury (1975) and Hudson and DeYoung (1978). Turner and Wescott (1981) discussed the geothermal energy potential of the region. Fisher (1982) and Decker and others (1988) described the petroleum potential of offshore basins adjacent to the Seward Peninsula.

1.3.2 Previous Studies at Cape Deceit

Kindle (1911), Sainsbury (1974), Dumoulin and Till (1985), and Till and others (1986) discussed the outcrops at Cape Deceit, although none of these authors offered detailed analyses. Kindle (1911) identified an Upper Silurian megafossil assemblage from Cape

Deceit including the rugose coral Amplexus and a lamellibranch bivalve he identified as similar to Megalodon found at White Mountain on the central Seward Peninsula. Sainsbury (1974) incorrectly suggested that the rocks at Cape Deceit are similar to limestones of the Mississippian Lisburne Group that crops out at Cape Thompson, on the Lisburne Peninsula, 270 km north of Deering (fig. 1). Dumoulin and Till (1985) presented data collected from outcrops in the field area, at and near Cape Deceit.

Dumoulin and Till (1985) interpreted breccia and bedded limestone intervals in the limestone member of the Smith Formation (section 3.3), located west of Cape Deceit, to be debris flows and turbidites deposited in a mid-shelf or deeper marine paleoenvironment. Conodonts extracted from these rocks indicate a middle Middle Silurian age.

Conodonts collected by Dumoulin and Till (1985) at Cape Deceit (section 3.4) and identified by Anita G. Harris (U.S. Geological Survey) are Ordovician through Devonian in age. Till and others (1986) correlated the rocks at Cape Deceit with the Ordovician through Devonian, black metalimestone and marble subunit of the Nome Group.

1.4 Regional Geology

The following discussion of the regional geology of the Seward Peninsula was synthesized from the work of Sainsbury (1969b, 1972, 1975), Hudson (1977), and Till (1982, 1984) and is summarized in Figure 3.

1.4.1 Terrane Analysis

1.4.1.1 Seward Terrane

The rocks of the Seward Peninsula (fig. 3) are divided into two stratigraphic terranes, the Seward and York terranes (Jones and others, 1981; and A.B. Till and J.A. Dumoulin, unpublished manuscript). The Seward terrane comprises all but the western part of the Seward Peninsula and is mostly underlain by metamorphic rocks which are subdivided into two lithostratigraphic units, the Kigluaik and Nome Groups. The Kigluaik Group includes the oldest rocks in the section and is named for exposures in cirques of the Kigluaik Mountains. Lithologically similar, probably age correlative, poly-deformed rocks form the cores of the Bendeleben and Darby Mountains of the central Seward Peninsula. The Kigluaik Group and other high-grade metamorphic rocks include amphibolite- to granulite-facies gneisses, schists, marbles and amphibolites and are at least Pre-Ordovician in age, based on their stratigraphic position below the Nome Group (Till and others, 1986).

The Nome Group (fig. 4) is named for a great thickness of limestone, graphitic and calcareous schist, and lesser intrusive greenstone and chloritic schist exposed in the Cape Nome and Norton Bay region (Brooks and others, 1901). The Nome Group occurs throughout the Seward Peninsula. It comprises multiply deformed greenschist- to amphibolite-facies slate, phyllite, schist,metacarbonates, orthogneiss and amphibolite. Previous studies of metamorphic petrography in the Nome Group have concentrated on rocks of the southern Seward Peninsula (Sainsbury and others, 1970; Till, 1982, 1984; Pollock, 1982; Forbes and others, 1984; Thurston, 1984, 1985; Sturnick, 1984). There, the Nome Group contains mineral assemblages representative of prograde, monocyclic, polyfacial high-pressure/temperature metamorphism (Thurston, 1985). Early low-temperature, high-pressure (blueschist facies) assemblages (sodic pyroxene, glaucophane and lawsonite in metabasites) were overprinted by high-pressure assemblages stable at slightly higher temperatures (greenschist facies = garnet, epidote and glaucophane in metabasites). Locally, retrograde, lower greenschist-facies assemblages were developed, probably due to uplift and erosion of overburden. The protoliths of the Nome Group include basinal organic-rich shale, mafic volcanic and intrusive rocks, shelf carbonate, and island-arc volcanic rocks. These early Paleozoic rocks were deposited in an area restricted from terrigenous input, thus favoring deposition of mainly

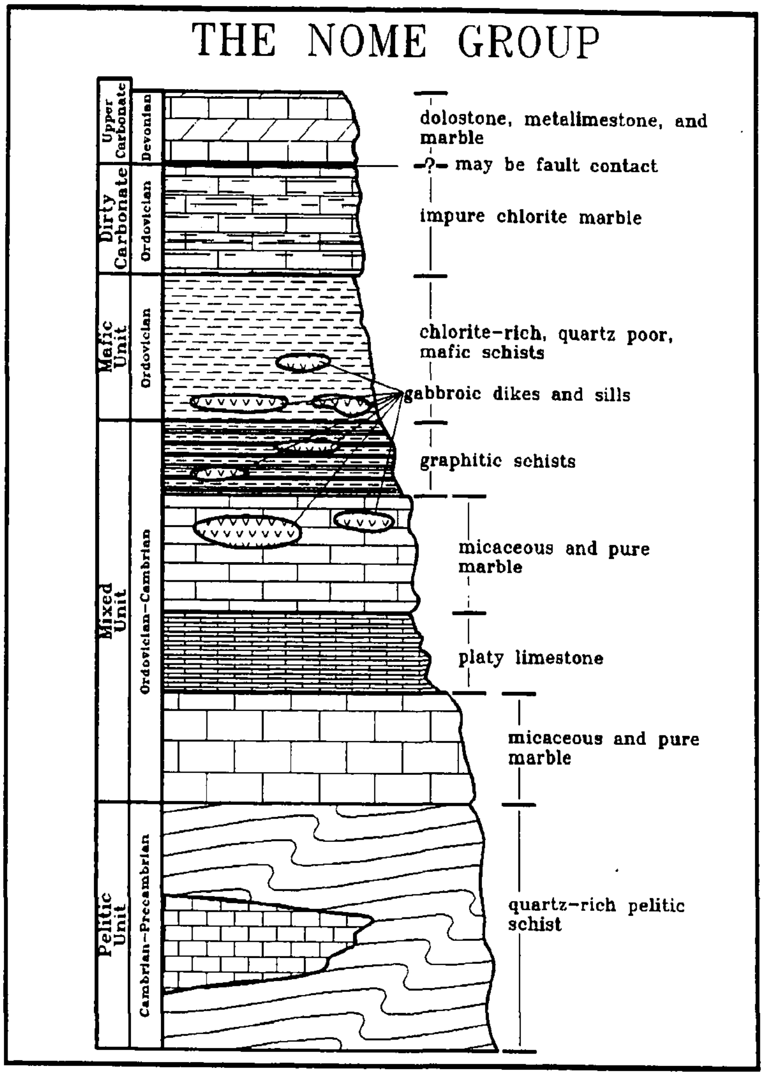

Figure 4. Generalized stratigraphic column of the Nome Group. Relative thicknesses of units on this figure are for comparison only since they may vary significantly throughout the region.

carbonate lithologies. Gabbroic dikes and sills intruding quartz-poor chloritic schists, represent a major mafic volcanic event. Carbonate deposition resumed after the volcanic event. Some platform and slope carbonate deposition continued on into the Devonian (Till and others, 1986). This combination of protoliths suggests that deposition occurred on and near a lower Paleozoic, passive, continental margin, possibly similar to the Sea of Japan. Conodonts and megafossils collected in the metacarbonates of the Nome Group range in age from Ordovician through Mississippian (J.A. Dumoulin, U.S. Geological Survey, oral communication, 1985).

1.4.1.2 York Terrane

A slightly deformed and metamorphosed sequence of Ordovician through Mississippian limestone, argillaceous limestone, dolostone, and fine-grained siliciclastic rocks makes up the York terrane. The York terrane is best exposed in the York Mountains of the western Seward Peninsula (fig. 1). These stratified rocks were thrust over partly coeval, low-grade metamorphic Nome Group (Till and others, 1986; C.E. Paris, oral and written communication, 1986).

1.4.2 Mesozoic Plutons

Mesozoic plutons of the Seward Peninsula are divided into three lithologic and age groups. The first group comprises plutons of widely varying composition (granite to syenite) which are present locally on the southeastern Seward Peninsula. These plutons are part of a regional plutonic belt that is primarily developed to the northeast of the Seward Peninsula in the Yukon-Koyukuk province (Miller, 1972). K-AR ages from this belt range from 93-108 Ma. The second group consists of biotite granodiorite and granite plutons that form large, mesozonal, batholithic complexes exposed primarily in the cores of the Kigluaik, Bendeleben, and Darby Mountains (Hudson, 1977). K-Ar ages from these plutons indicate cooling between 80 and 100 Ma. The last group is represented by small, Early Cretaceous (70-80 Ma), granitic and alkalic intrusives which crop out on the western Seward Peninsula. These granitic stocks are the hosts of economically important tin deposits.

1.4.3 Cretaceous-Tertiary Sediments

Cretaceous and early Tertiary sedimentary rocks occur in small, isolated outcrops in a narrow, north-south trending fold belt extending north along the Kugruk River east of the Darby Mountains. This fold belt parallels the Kugruk fault zone (Sainsbury, 1974; A.B. Till and J.A. Dumoulin, unpublished manuscript), a complex of north-south trending vertical faults which extends from Norton Sound to Kotzebue Sound (fig. 1). The sediments occurring here are primarily non-marine conglomerates and sandstones containing carbonate and mafic-igneous clasts. They are interbedded with locally-thick coals, notably along Chicago Creek (fig. 2).

1.4.4 Tertiary Basalts

Three basalt-flow units occur within the central Seward Peninsula. The oldest basalts are the Imuruk Volcanics. They have been dated by K-Ar methods at 2.2 Ma (Turner and Wescott, 1981) and 5.85 Ma (Hopkins and others, 1971). The next younger unit is the Gosling Volcanics which were dated by K-Ar methods at 0.82 and 0.91 Ma (Turner and Wescott, 1981). The youngest basalts are from the Lost Jim lava flow. These fresh-looking basalts are probably 10,000 to 15,000 years old (Hopkins, 1963).

1.4.5 Tectonic History

High-grade, intensely deformed, metamorphic rocks in the core of the Kigluaik Mountains record the oldest tectonic event which affected the Seward Peninsula. Rb/Sr age dates of these rocks indicate a late Precambrian thermal event (735 Ma Rb/Sr whole-rock isochron; Bunker and others, 1979). Other intensely deformed Precambrian rocks may exist in scattered areas throughout the Seward Peninsula (Gardner and Hudson, 1984). Metaigneous intrusive rocks within the Nome Group have Devonian Rb/Sr ages (Till, 1982) and may correlate with a Devonian orogenic event.

The Seward Peninsula is part of an Arctic landmass that has extended from the U.S.-Canada border into Siberia since Middle Devonian time (Tailleur and others, 1967). Rapid, deep burial of the Arctic landmass occurred in Late Jurassic time. Tectonic thickening over the Seward Peninsula and Brooks Range progressed from west to east as this Arctic landmass collided with the Yukon-Koyukuk terrane. This collision and burial event was responsible for blueschist facies metamorphism (Forbes and others, 1984) and the reequilibration of K-Ar systems in most metamorphic rocks on the Seward Peninsula (Armstrong and others, 1986). Approximately 30 km of material was thrust on top of the Nome Group to produce the metamorphism observed (A.B. Till and J.A. Dumoulin, unpublished manuscript).

Till and Dumoulin (unpublished manuscript) suggest that two separate compressional events may have affected the area. The first was a Late Jurassic to early Cretaceous, northeast-directed compression event synchronous with the development of the fold and thrust belt of the Brooks Range when an island-arc complex collided with the Arctic landmass (Roeder and Mull, 1978; Friedman and others, 1984). The second was an east-west compression event centered in the Bering Straits area. These two events may have been responsible for conflicting interpretations of thrust vergence obtained from studies of the structural elements of Paleozoic rocks of the Seward Peninsula, and for similar problems in the western Brooks Range.

Neogene north-south extension (Gardner and Hudson, 1984) resulted in the extrusion of the Imuruk Basin basalt flows. The Kigluaik, Bendeleben, and Darby Mountains are regional horst blocks that formed during this time period.

2.0 Stratigraphic Nomenclature

The Deceit Formation is the lithostratigraphic name proposed by Ryherd and Paris (1987) for three outcrops of limestone, dolostone and shale that crop out at and near Cape Deceit. I propose that the use of this name be discontinued and that the name Smith Formation, be substituted in its place. This change is necessary to avoid confusion with a Pleistocene, terrestrial sediment interval located at Cape Deceit previously named the Cape Deceit Formation by Guthrie and Matthews (1971). This usage was unknown to Ryherd and Paris (1987) when they initially proposed the name Deceit Formation.

The name Smith Formation (fig. 5) is derived from Smith Creek which parallels the coast in the field area (fig. 6). No outcrops of the Smith Formation occur on Smith Creek, but use of the name was necessary because of the lack of more suitable geographic features in the field area that are not currently in use. Justification for the assignment of formal lithostratigraphic nomenclature to the Smith Formation includes: (1) its unique and relatively undeformed nature with respect to the surrounding rocks, (2) its location in an important geographic position between other lower Paleozoic sedimentary rocks of the western Seward Peninsula and the western Brooks Range, (3) its utility as a map unit at a scale of 1:63,360 and 1:250,000, and (4) its fauna of regionally important fossil graptolites and conodonts.

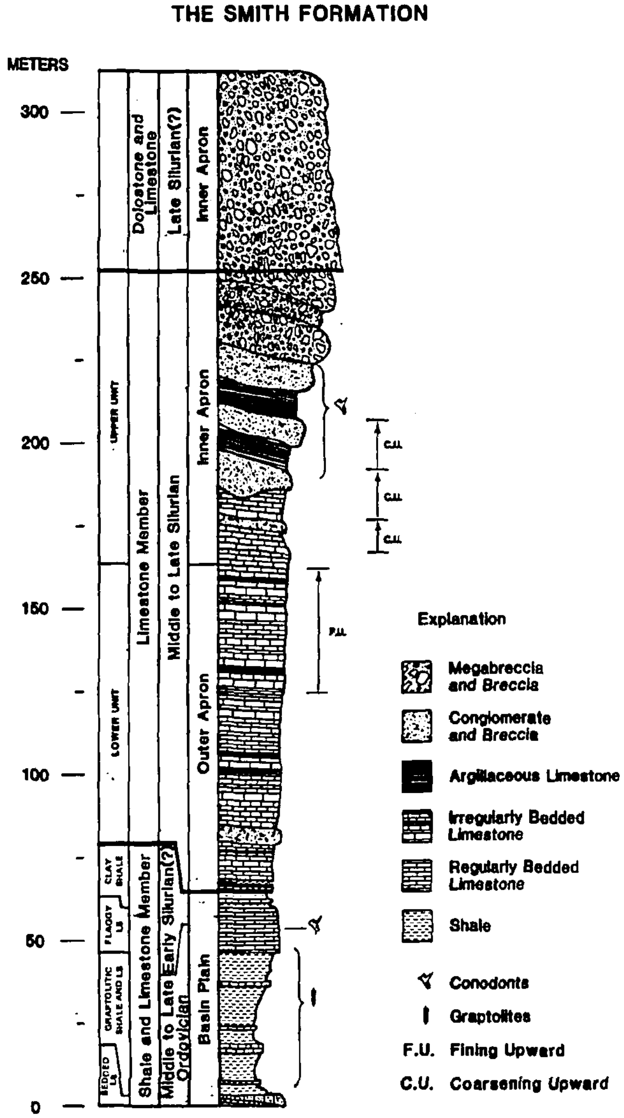

Figure 5. Reconstructed stratigraphic column of the Smith Formation showing age of sections and environmental interpretations.

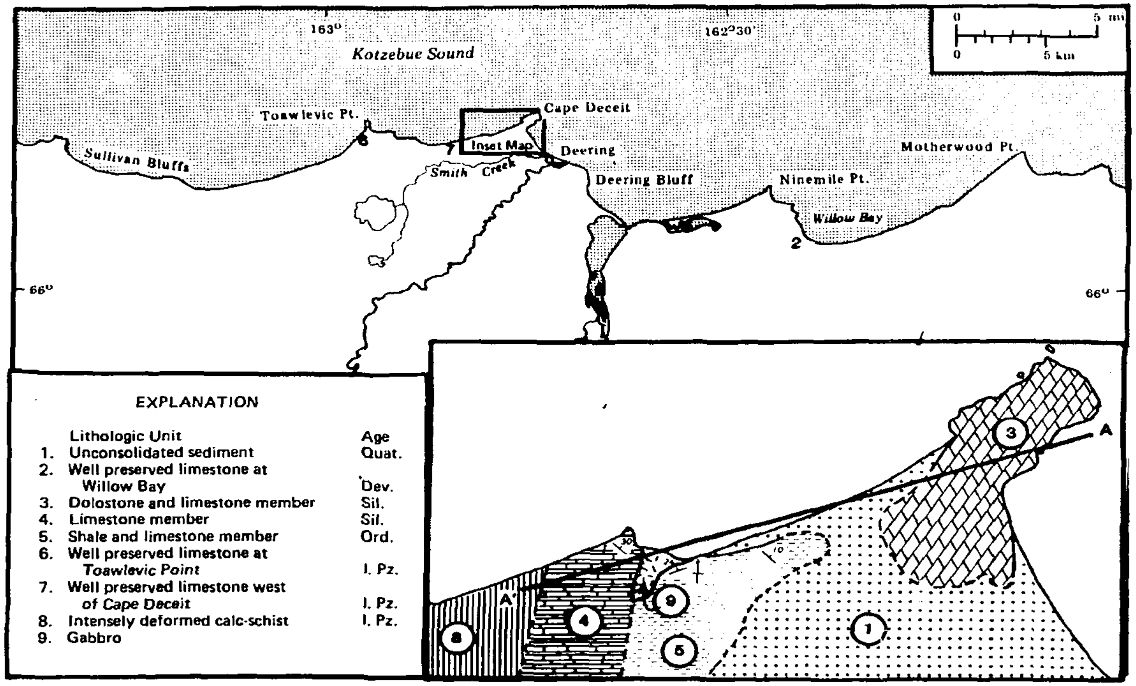

Figure 6. Location and geologic map of the field area. Important outcrops are identified. Line A-A' is line of cross-section shown in Figure 7.

The Smith Formation is comprised of three informally named members. In ascending order they are (1) the shale and limestone member, (2) the limestone member, and (3) the dolostone and limestone member. Figure 6 shows the locations of the three sections that compose the composite-stratotype of the Smith Formation. Also shown are the locations of other outcrops discussed in this text and the geology of the area around the Smith Formation. Figure 7 schematically shows their structural relationships.

Section 3.0, below, summarizes the important descriptive aspects of the Smith Formation. Tables 1, 2, 3, and 4 include the detailed descriptive characteristics of the Smith Formation. Section 4.1 provides interpretations of the depositional environments.

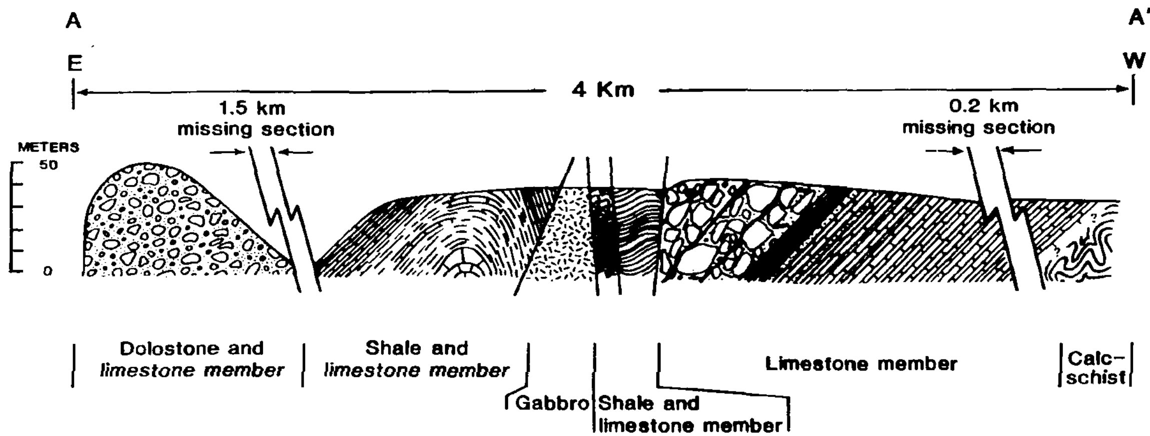

Figure 7. Cross-section of the Cape Deceit area showing the structural relationships of members of the Smith Formation.

Table 1. Descriptive characteristics of the lower shale and limestone member of the Smith Formation.

MEMBER	SHALE AND LIMESTONE MEMBER	
SECTION THICKNESS	70 m (230 ft)	
UNIT	CHANNEL LIMESTONE	GRAPTOLITIC SHALE AND LIMESTONE
UNIT THICKNESS	2.4 m (8 ft)	54 m (177 ft)
LITHOLOGY	Limestone Argillaceous Limestone	Shale Limestone Chert
CRYSTAL SIZE	Very coarse limestone, fine argillaceous limestone interbeds.	Clay- and silt size ahsle, coarse limestone, microcrystalline chert.
COLOR	Gray to gray-black limestone.	Brown to black shale, weathers to brown and red. Dark gray to gray-black limestone. Gray-black chert.
SEDIMENTARY STRUCTURES AND FABRICS	Parallel laminations, graded bedding, rip-up clasts. Clasts are isolated (floating) in matrix and are usually flat laying and parallel to bedding. Clasts are black, platy shale up to 1 cm (.4 in) thick and 9 cm (3.6 in) in diameter.	Thinly laminated shales, cross-bedding and graded bedding in limestone.
BEDDING CHARACTER	Up to 1 m (3.3 ft) thick limestone. Up to 1 cm (.4 in) thick argillaceous limestone. Thickness varies considerably and is indicative of channeling in the limestone. Argillaceous limestone drapes over tops of the limestone beds. Limestone and argillaceous limestone occurr in together	Shale averages less than 1 cm (.4 in) thick, up to 2.5 cm (1 in) thick. Limestone beds up to 45 cm (18 in) thick. Some limestone beds pinch out and form lenses as small as 1 m (3.3 ft) across and 2 cm (.8 in) thick. Most shale beds are laterally continuous but thicken and thin along strike. Chert beds are up to 5 cm (2 in) thick and irregularly bedded.
CONTACTS	Confomable (?) with overlying graptolitic shale and limestone unit. Bottom of this unit not exposed.	Conformable with overlying flaggy limestone unit. Conformable with channel limestone unit below.
OTHER		Shale has slaty olevage parallel to bedding and at several other orientations.
FOSSILS	None.	Graptolites found at 6 horizons and in float.
AGE	?	Middle Ordovioian through Upper Ordovician. (Caradocian through Ashgillian)

Table 2. Descriptive characteristics of the upper shale and limestone member of the Smith Formation.

MEMBER	SHALE AND LIMESTONE MEMBER	
SECTION THICKNESS	70 m (230 ft)	
UNIT	FLAGGY LIMESTONE	CLAY SHALE
UNIT THICKNESS	10.5 m (35 ft)	3.6 m (12 ft)
LITHOLOGY	Limestone Argillaceous Limestone	Clay Shale Limestone Argillaceous Limestone
CRYSTAL SIZE	Coarse limestone, fine argillaceous limestone.	Clay shale. Coarse limestone, argillaceous limestone.
COLOR	Gray-black to black limestone. Red to balck argillaceous limestone.	Gray to red clay shale. Gray-black to black limestone. Red to black argillaceous limestone.
SEDIMENTARY STRUCTURES AND FABRICS	Thinly laminated. Fine graphitic partings.	Thinly laminated shales and limestone. Limestone has texture similar to flaggy limestone unit.
BEDDING CHARACTER	Limestone is 3-15 cm (1.2-5.4 in) thick. Less than 1 cm (.4 in) thick argillaceous limestone. Laterally continuous, parallel and planar bed surfaces.	Clay shale is thinly bedded and very friable. Limestone is 3-15 cm thick (1.2-5.4 in) thick, laterally continuous, parallel and planar, and similar in character to limestone beds in the flaggy unit.
CONTACTS	Conformable with overlying clay shale unit. Conformable with graptolitic shale unit beneath.	Top not exposed. Conformable with flaggy limestone unit below..
OTHER	Microscope analysis allowed the interpretation of original grain size, believed to be silt and clay size.	Mica flakes are abundant on parting surfaces.
FOSSILS	Graptolites found at base of this unit. Conodonts found at one horizon.	None.
AGE	Ordovician.	?

Table 3. Descriptive characteristics of the limestone member of the Smith Formation.

MEMBER	LIMESTONE MEMBER	
SECTION THICKNESS	185 m (607 ft)	
UNIT	LOWER UNIT	UPPER UNIT
UNIT THICKNESS	99 m (324 ft)	86 m (283 ft)
LITHOLOGY	Limestone Dolostone Argillaceous Limestone	Limestone Argillaceous Limestone
CRYSTAL SIZE	Medium to coarse limestone and dolostone. Fine argillaceous limestone.	Medium to coarse limestone. Fine argillaceous limestone.
COLOR	Red-brown argillaceous limestone and dolostone. Medium gray-brown to black limestone and dolostone.	Gray to red brown limestone. Gray-black to red-brown argillaceous limestone.
SEDIMENTARY STRUCTURES AND FABRICS	Coarsens and thickens upward. Contains fining and thinning upward cycles, 5 to 30 m (15 to 100 ft) thick. Thick parallel laminations, rip-ups, loading features, graded bedding, cross-bedding, and mud drapes. Clasts are black platy limestone up to 5 cm (2 in) thick and 20 cm (8 in) in length. They Occur only in a single isolated bed.	Coarsens and thickens upward. Contains coarsening and thickening upward cycles, 5 to 15 m (15 to 50 ft) thick. Limestone exhibits parallel laminations, graded bedding, rip-up clasts, and loading features. The graded bedding is well defined in the lower portion of this unit, but is less common or has been masked by recrystallization in the top part of the upper unit. Two clast types are present. Black platy limestone clasts up to 10 cm (4 in) thick and .75 m (2.5 ft) in length. Gray, brown and white rounded clasts up to 4 m (15 ft) across.
BEDDING CHARACTER	Beds have sharp erosional bases and gradational tops. Bedding thicknesses vary from less than 1 cm (.25 in) for the argillaceous limestone beds to 1 m (3.3 ft) for the crystalline limestone.	Many of the coarsely crystalline, graded, limestone beds in the upper unit have undulating tops that have the appearance of large scale ripple (megaripple) forms. These undulations have amplitudes of 10 to 12 cm (4 to 5 in) and wavelengths of .6 to 1.5 m (2 to 5 ft). Most beds have erosional bases. Some evidenoe channel scour and fill is seen.
CONTACTS	Top of this unit is truncated by a fault. Uppermost fining and thinning upward cycle was used to determine the top of this unit. Base of this unit is truncated by a fault. Base is in fault contact with structurally complex calc-schist.	Top of this unit is not exposed. Base of this unit is in fault contact with underlying lower unit.
OTHER	Numerous high angle faults with undetermined offset are recognized throughout this section.	
FOSSILS	Conodonts found at one horizon only.	Conodonts found at three horizons.
AGE	Ordovician through Silurian.	Middle to Upper Silurian. (Wenlockian to Ludlovian)

Table 4. Descriptive characteristics of the dolostone and limestone member of the Smith Formation.

MEMBER	DOLOSTONE AND LIMESTONE MEMBER
SECTION THICKNESS	61 m (200 ft)
UNIT	
UNIT THICKNESS	
LITHOLOGY	Dolostone Limestone
CRYSTAL SIZE	Medium to coarse dolostone and limestone.
COLOR	Gray, yellow, yellow-brown and light brown dolostone and limestone.
SEDIMENTARY STRUCTURES AND FABRICS	No sedimentary structures are present. Fabric varies in the proportion of matrix to clasts. Parts of the outcrop are clast supported, usually containing with clasts that are less than 5 cm (2 in) in diameter. Most of the outcrop is matrix supported. Matrix varies from dense coarsely crystalline dolostone to sucrosic limestone. More sucrosic matrix appears to be related to hydrous alteration. Clasts are light yellow to brown, spherical and angular to subangular. Some clasts are shell and crinoid stem fragments.
BEDDING CHARACTER	No bedding recognized anywhere on this outcrop.
CONTACTS	Stratigraphic top and bottom were not determined. No contacts with other units were identified.
OTHER	A low angle, mylonitized fault surface forms the top (topographic) of the outcrop. Many high and low angle faults of undetermined displacement are present throughout the outcrop.
FOSSILS	Age based upon previously documented occurrences of conodonts, bivalves, and corals.
AGE	Silurian through Devonian.

3.0 The Smith Formation

3.1 Descriptive Techniques and Definitions

3.1.1 Recrystallization of Primary Fabric

Within the Smith Formation, the shales show the least evidence of recrystallization while the limestones are almost completely recrystallized. Because of the recrystallization, the description of these rocks is in terms of crystallinity rather than depositional texture. Where preservation of ghosts of grains and clasts occurs, the original grain size was inferred so that interpretations of the depositional history could be made.

Because no established guidelines exist for making interpretations of original grain size in recrystallized carbonate rocks, a set of hypotheses was established for this purpose. Carbonate rocks were analyzed as thin-sections, hand samples and outcrops. The minerals found commonly in the Smith Formation were placed in a hierarchy based on their susceptibility to recrystallization (fig. 8). Hypotheses developed for establishing original grain size in carbonate rocks metamorphosed to greenschist facies include: (1) when minerals are recrystallized during static burial metamorphism, the grain size increases (Blake and others, 1967); (2) the mineralogy of a metasedimentary rock is related to the mineralogy of the original sedimentary rock; (3) there is a predictable relationship between size and mineralogy in

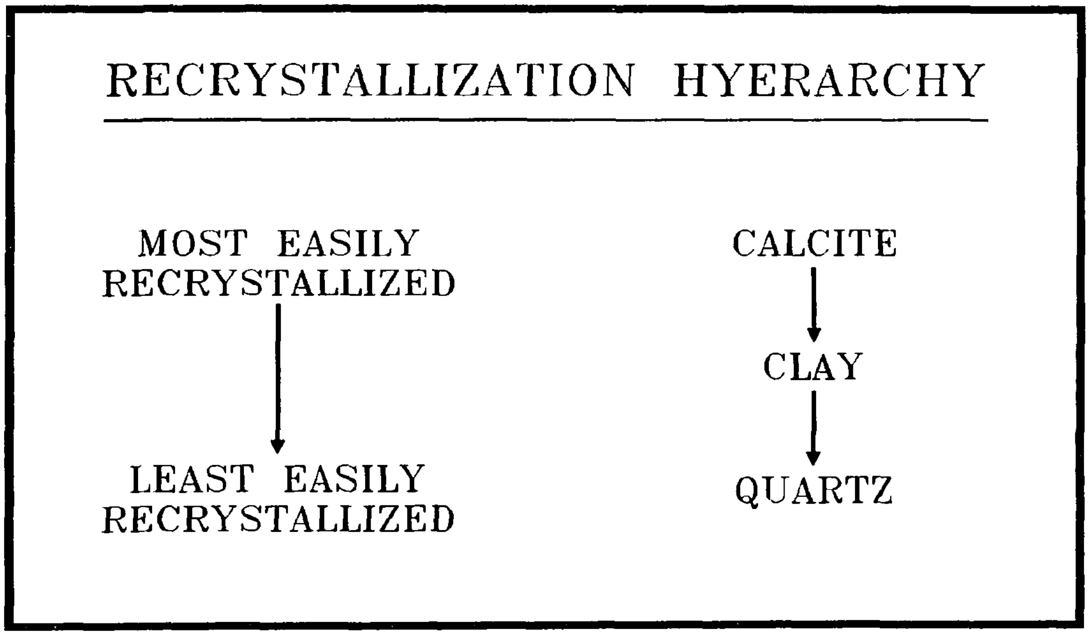

Figure 8. Recrystallization hierarchy used in defining the original sedimentary rock fabric of the Smith Formation.

siliciclastic sediments; and (4) the size of a sedimentary structure reflects the relative size of the grains that make it up.

The following examples will demonstrate how the hypotheses were used to interpret the Smith Formation:

1. The presence of large amounts of clay, mica, and/or clay- and silt-size graphitic material, evenly disseminated throughout a carbonate rock when viewed in thin-section, indicates that the original deposit was primarily clay- or silt-size particles.

2. Thin, repetitively bedded, homogeneous, argillaceous and micaceous carbonate was originally carbonate mud with high clay content.

3. Parallel laminations indicate original deposition as either sand- or silt-size sediment deposited in an upper flow regime, or clay-size sediments deposited in a lower flow regime.

4. Cross-bedding and megaripples indicate a predominance of sand-size particles deposited under lower flow regime conditions.

Commonly, larger scale aspects of texture and bedding are visible. Conglomeratic clasts greater than about 1.0 cm in diameter occur in the Smith Formation and the original sizes of the clasts discussed in the text are from actual measurements. The original bedding character of the limestone member and the shale and limestone member is obvious in the outcrops despite recrystallization. There is no obvious bedding in the dolostone and limestone member.

3.1.2 Depositional Processes

3.1.2.1 Peri-Platform Ooze

Peri-platform ooze is a term introduced by Schlager and James (1978) for sediments that accumulate on platform slopes and proximal basin plains adjacent to carbonate platforms. Peri-platform ooze is fine-grained carbonate mud that is derived from the nearby platform and is equivalent to, and may be mixed with, hemipelagic sediments. Mullins (1983) suggests that peri-platform oozes originate as carbonate platform sediments that were eroded by storms and carried in suspension into deeper water by ocean currents. The fine-grained sediments moved laterally along surface layers and/or mid-water intervals of density contrast before settling out by gravitational processes and/or fecal pelletization by zooplankton.

3.1.2.2 Turbidites

Submarine turbidity flow is a major sediment transport mechanism in the Smith Formation. Depositional units created by turbidity flows usually show distinct boundaries. They have planar bases and tops, or channelized bases and planar tops. The degree of sediment sorting in turbidites varies, but characteristic sedimentary structures as defined by Bouma (1962) are important in their identification. Turbidites may or may not have mud matrices. Commonly, clasts are mixed together during movement and supported by turbulent suspension. Turbidity flows are capable of moving sediment down very low-angle slopes for long distances.

Bouma's (1962) model for turbidite deposition serves as a descriptive tool for the Smith Formation. Bouma differentiated a sequence of sedimentary structures to correlate with progressively decreasing flow velocities. The five parts of a turbidite are abbreviated as follows:

1) T_a, massive graded bedding,
2) T_b, upper flow-regime planar lamination,
3) T_c, lower flow regime rippled cross-laminations,
4) T_d, lower flow-regime planar laminations,
5) T_e, suspension deposition.

3.1.2.3 Debris Flows

A debris flow is sediment supported above the sediment-water interface by matrix strength and buoyancy (Cook and others, 1972; Middleton and Hampton, 1976), allowing larger clasts to "float" along in a muddy matrix (Cook and Mullins, 1983). Debris flows show distinct depositional boundaries. They have planar bases and tops, or planar bases and hummocky tops. Debris flows commonly are poorly sorted and not graded. They usually have muddy matrices with clasts mixed together and supported during movement by some type of non-turbulent mechanism. Debris flows represent material transported down low-angle slopes over shorter distances than turbidites.

3.1.3 Sedimentary Facies

Mutti and Ricci Lucchi (1972) established a framework of sediment facies (Facies A through G) for the definition of turbidite depositional environments. A modification of Mutti and Ricci Lucchi's (1972) facies was used in this study and is defined in Appendix I. A summary of the facies follows:

Facies A--coarse-grained, poorly sorted sandstone and conglomerate that may contain muddy or shaly interbeds;

Facies B--thick to massive, medium-fine to coarse sandstone;

Facies C—laterally continuous, medium to fine sandstone with minor amounts of homogeneous mud or shale;

Facies D—fine and very fine sandstone, mud, and shale, having marked lateral continuity;

Facies E—similar to Facies D except with higher sand:shale ratio, thinner and more irregular beds, and laterally discontinuous beds;

Facies F--includes submarine slides, mud-supported megabreccia, and mud-supported conglomerate that are deformed as slides, slumps, mudflows, debris flows, grainflows, and high-density turbidity currents;

Facies G--peri-platform ooze, mud, shale and marl that can be more or less silty and calcareous, with indistinct or poorly developed, smooth, parallel bedding.

3.2 Conodont Alteration Index

The Smith Formation is slightly metamorphosed, with conodont alteration index (CAI) values ranging from 5.5 to 7.5 (Timothy Carr, Atlantic Richfield Company, written communication, 1985) indicating temperatures in the range of 400°-700°C. This is equivalent to the temperature of greenschist to amphibolite facies metamorphism. Petrographic analysis (discussed in section 5.1) and work by Dumoulin and Till (1985) and Till and others (1986) support this association between CAI values and metamorphic facies.

3.3 Shale and Limestone Member

The shale and limestone member crops out 1.5 km west of Cape Deceit (Fig. 6). The exposure is 70 m thick and is divided into four lithologic units (fig. 9). In ascending order they are bedded limestone, graptolitic shale and limestone, flaggy limestone, and clay shale. Figure 7 shows folding and structural complications evident in the outcrop. The best exposure of the shale and limestone member occurs in an anticlinal structure which plunges N5°E. Small-scale (amplitude and wavelength of 5 to 50 cm) folds occur at this unit. The contacts of the shale and limestone member are not exposed; therefore stratigraphic relationships between overlying and underlying units can only be implied. Tables 1 and 2 give a detailed description of the shale and limestone member.

3.3.1 Bedded Limestone Unit

The only exposure of the bedded limestone unit is in the core of an anticline. The outcrop is only 3 m by 3 m, thus lateral variations could not be determined. The unit consists of dark, coarsely crystalline limestone interbedded with laminated, finely crystalline, argillaceous limestone. The thickness of the coarsely crystalline limestone beds varies from 4 cm up to 1 m suggesting a depositional lobe or progradational depositional environment.

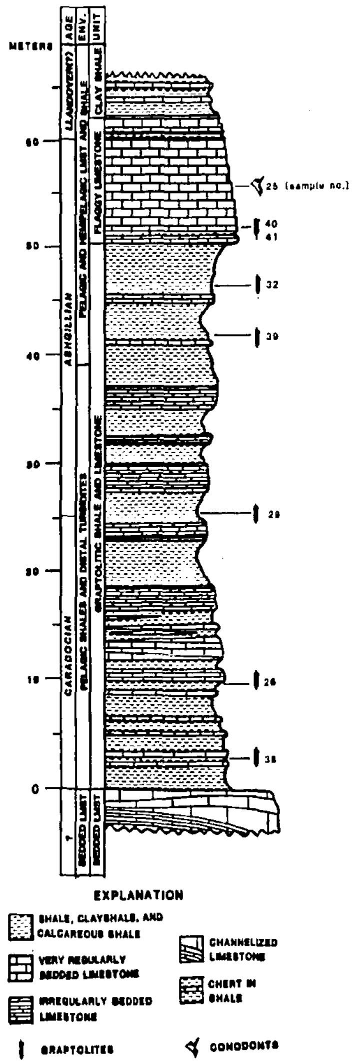

Figure 9. Shale and limestone member diagram showing graptolite and conodont sample horizons.

Thick graded beds (T_a), abundant shale rip-ups, upper flow regime parallel laminations (T_b), and erosional contacts are sedimentary structures which were found in the bedded limestone unit. These features indicate deposition as turbidites, although the T_c-T_e deposits of the standard turbidite sequence are typically missing. Originally, the thin, parallel laminated, argillaceous limestone and coarsely crystalline limestone interbeds (T_d-T_e) between the more massive coarsely crystalline limestone beds were calcareous shale and fine calcarenite. This description of the bedded limestone indicates deposition as Facies C.

3.3.2 Graptolitic Shale and Limestone Unit

The 54 m thick graptolitic shale and limestone unit is in abruptly conformable contact with the bedded limestone unit. The lithology is dominantly shale and limestone with subordinate chert. Shale beds are typically less than 1 cm thick, but may be as thick as 2.5 cm. Shale beds are thinly laminated and laterally continuous but thicken and thin along strike. Coarsely crystalline limestone beds are normally dark gray to gray-black and laterally continuous, reaching a maximum thickness of 45 cm. Limestone beds also thicken, thin, and pinch out along strike at some locations. The thicker limestone beds are graded and one bed shows visible cross-laminations. The thinner beds pinch out or form long (more than 1 m), thin (less than 2 cm) lenses. Chert occurs as discontinuous beds and boudins up to 7 cm thick.

The fine-grained siliciclastic and calciclastic sediments with parallel laminations and bedding represent T_d-T_e and hemipelagic mud deposition. The chert beds and boudins represent pelagic deposits of siliceous ooze. Graded and parallel laminated, coarsely crystalline limestone beds are T_a-T_b turbidites. Limestone beds are also locally cross-laminated and exhibit the complete Bouma sequence (T_a-T_e). The combination of predominant hemipelagic mud, pelagic siliceous ooze, and subordinate turbidites indicates deposition as Facies D and E.

No conodonts occur in the graptolitic shale and limestone unit. Till and others (1986) reported probable recrystallized radiolaria in chert in the lower portion of this unit, but noted that preservation is too poor for specific identification.

Graptolites were discovered at several horizons in the unit by Michael Churkin (Atlantic Richfield Company) and I in 1985. Although not well preserved, they are abundant and cover the bedding surface at some horizons. Often, a brownish-red coating of limonite is all that remains on the surface, indicating that the graptolites may have originally been pyritized and later oxidized and weathered. However, no fresh specimens of pyritized graptolites were seen.

3.3.3 Flaggy Limestone Unit

The flaggy limestone unit conformably overlies the graptolitic unit. It is 10.5 m thick and is composed of distinctive, thin- to medium-bedded, coarsely crystalline, limestone with thin interbeds of argillaceous limestone (fig. 10). The coarsely crystalline limestone beds range from 3 to 15 cm in thickness and the argillaceous limestone beds are less than 1 cm thick. These beds exhibit no notable lateral variation in thickness across the outcrop.

Petrographic analysis of the coarsely crystalline limestone revealed fine organic material included within the calcite that had recrystallized around it (fig. 11). This indicates that the original grains were clay- and silt-size material and that the crystalline texture is not indicative of the original grain size (for explanation of interpretive criteria see section 3.1).

The flaggy limestone apparently represents peri-platform ooze. Characteristics of the flaggy limestone that indicate that it was deposited as peri-platform ooze are 1) the relatively pure carbonate composition, 2) the originally fine-grained nature of the rocks evident in thin-section, 3) the significant amount of evenly

Figure 10. Outcrop of the shale and limestone member. Note regular bedding thickness and planar bedding surfaces.

Figure 11. Photomicrograph of a sample from the flaggy limestone unit showing disseminated, fine graphitic material indicative of its original silt- or clay-size (scale: 1=.0042).

disseminated, silt-size and smaller particles of organic material, 4) the unusually regular bedding thicknesses, and 5) the planar surfaces of the bedding. All of these features are typical of peri-platform ooze (Mullins, 1983).

One graptolite fossil was discovered in the lower part of this unit and one sample from this unit yielded conodonts. The age of these fossils will be discussed in Section 3.3.5.

3.3.4 Clay Shale Unit

The clay shale unit, consisting of 3.6 m of calcareous clay shale with about 10% thin (3-15 cm thick), coarsely crystalline limestone interbeds, gradationally overlies the flaggy limestone unit. The limestone beds resemble those in the flaggy limestone unit. They are regularly bedded with no lateral variation within the limited exposures.

The clay shale unit represents deposition in quiet water far from major sediment sources. The clay shales appear to represent hemipelagic sediments because they gradationally overlie the flaggy limestone which also represents hemipelagic sediments. The thin limestone beds within the unit are interpreted to be peri-platform ooze because they are similar in character to the regularly bedded flaggy limestone. The clay shale unit differs from the underlying flaggy limestone unit mainly by an increased ratio of argillaceous and siliceous material to carbonate; however it still represents deposits of Facies G.

3.3.5 Chronostratigraphy of the Shale and Limestone Member

Ten samples containing graptolite fossils were collected from 7 stratigraphic horizons in the shale and limestone member (fig. 9) and 11 additional samples were collected from float near the same outcrop. The abundance of graptolites varied through the fossiliferous interval, but several faunas were extremely abundant. The graptolites were described and identified by Claire Carter of the U.S. Geological Survey. Sixteen species were positively identified in the samples from this section (fig. 12), representing a biostratigraphic succession comprising four graptolite zones of Late Ordovician, Caradocian through Ashgillian Age (fig. 13). No age correlative graptolite faunas are known from elsewhere on the Seward Peninsula or from the Baird Mountains of the Western Brooks Range (Claire Carter, oral communication, 1985).

An estimate of the sedimentation rate for the shale and limestone member can be calculated based on the ages and positions in the section of graptolite horizons. Fifty-two meters separate the oldest and youngest graptolite faunas in the section. The oldest sample is within the Climacograptus peltifer Zone (454 to

	Climacograptus bicornis Zone				Middle Ordovician			Orthograptus amplexicaulis intermedius Zone		Middle Ordovician		Orthograptus quadrimucronatus	Climacograptus supernus Zone, P. pacificus subzone			Late Ordovician				
Genus and Species / Collection Number	38	36f	22f	21f	20f	24f	23f	25	26	37f	27f	29	39	35	34	33	32	31f	30f	40f
Corynoides calicularis Nicholson	X																			
Dicranograptus sp.							X					?								
Dicellograptus alector Carter												X								
sp.												X								
Cryptograptus tricornis (Carruthers)	X			X																
Amplexograptus sp.	X																			
Climacograptus bicornis (Hall)	X	X	X	X																
caudatus Lapworth								X	X											
cf. C. normalis Lapworth																				X
pogrebovi Koren & Sobolevskaya													X							
cf. C. pogrebovi															X					
spiniferus Ruedemann									X											
sp.									X					X				X	X	
? sp.						X									X	X	X			
Glyptograptus ? sp.											X									X
Orthograptus cf. O. Amplexicaulis (Hall)								X	X			X								
calcaratus calcaratus Lapworth	X																			
calcaratus subsp. indet.					X		X													
quadrimucronatus (Hall)												X								
? sp.										X										
Paraorthograptus pacificus pacificus (Ruedemann)													X							
Lasiograptus harknessi (Nicholson)	X																			
? sp.				X																

Figure 12. Genus and species of graptolites from shale and limestone unit cross-referenced with collection number , biozones and age data (written communication from C. Carter, U.S. Geological Survey).

Ma	AGE	ALASKA (this paper)	TEXAS (Berry, 1960)	AUSTRALIA (VandenBerg, 1981)	BRITISH ISLES (Williams, 1982; 1983)		N.E. USSR (Koren' and others, 1983)	
438	ASHGILLIAN	*P. pacificus*	*Dicellograptus complanatus*	Bolindian	*P. pacificus*	*D. anceps*	*P. pacificus*	*C. supernus*
		?			*D. complexus*		*C. longispinus*	
					D. complanatus		*Orthograptus quadrimucronatus*	
448	CARADOCIAN	*O. quadrimucronatus*	*Orthograptus quadrimucronatus*	Ea4	*Pleurograptus linearis*			
		?		Ea3	*Dicranograptus clingani*			
		Orthograptus cf. *O. amplexicaulis*	*Orthograptus truncatus intermedius*	lower Eastonian Ea1–Ea2	*Climacograptus wilsoni*	*Diplograptus multidens*		
		Climacograptus bicornis	*Climacograptus bicornis*	upper Gisbornian	*Climacograptus*			

Figure 13. Biostratigraphic correlation chart for graptolites of the shale and limestone member of the Smith Formation (written communication from C. Carter, U.S. Geological Survey).

458 Ma; absolute age correlations from Harland and others, 1983) and the youngest sample is within the Dicellograptus anceps Zone (438 to 447 Ma). Thus, a time interval of 7-20 Ma is bracketed by these two samples. Using these data, the calculated rate of sediment accumulation is between 0.0026 and 0.0074 km/Ma. This is an acceptable sedimentation rate for a basin plain near the base of a carbonate apron (H.E. Cook, U.S. Geological Survey, oral communication, 1985). There are about 12.2 m of exposed section above the samples collected from the highest stratigraphic position, suggesting that sedimentation in the shale and limestone member probably continued for an additional 1.6 to 4.6 Ma.

Because the Ordovician/Silurian boundary is dated at 438 Ma, it is possible that this series boundary is recorded in the upper part of the shale and limestone member. If this is the case, then the Smith Formation correlates in age with an Ordovician-Silurian sequence of platform carbonate rocks in the York Mountains of the western Seward Peninsula (Sainsbury and others, 1971).

The shale and limestone member also contains a poorly preserved conodont fauna (fig. 9) that is Ordovician in age (Timothy Carr, written communication, 1985). This age agrees with the ages obtained from the graptolite faunas described above.

3.4 Limestone Member

The limestone member crops out in cliffs along the coast 3 km west of Cape Deceit (fig. 6). The exposed section is 185 m thick and is composed of carbonate megabreccia, breccia, and coarsely and finely crystalline limestone. In general, the beds coarsen and thicken upward. The limestone member can be logically divided into a lower unit characterized by fining- and thinning-upwards sequences and an upper unit having coarsening- and thickening-upwards sequences (fig. 14). Stratigraphic relationships between the limestone member and overlying and underlying units is unknown because the contacts of this unit are not exposed.

3.4.1 Lower Unit

The lower unit consists of repetitively interbedded, coarsely crystalline and finely crystalline, argillaceous limestone and dolostone (fig. 15). Overall, the grain size coarsens upward, but smaller-scale individual sequences (up to 15 m thick) fine upwards. The highest fining- and thinning-upward package in the section defines the top of the lower unit.

The repetitively bedded, coarsely crystalline and finely crystalline limestones and dolostones of the lower unit of the limestone member were deposited as carbonate turbidites and hemipelagic mud. Thick accumulations of turbidites with graded

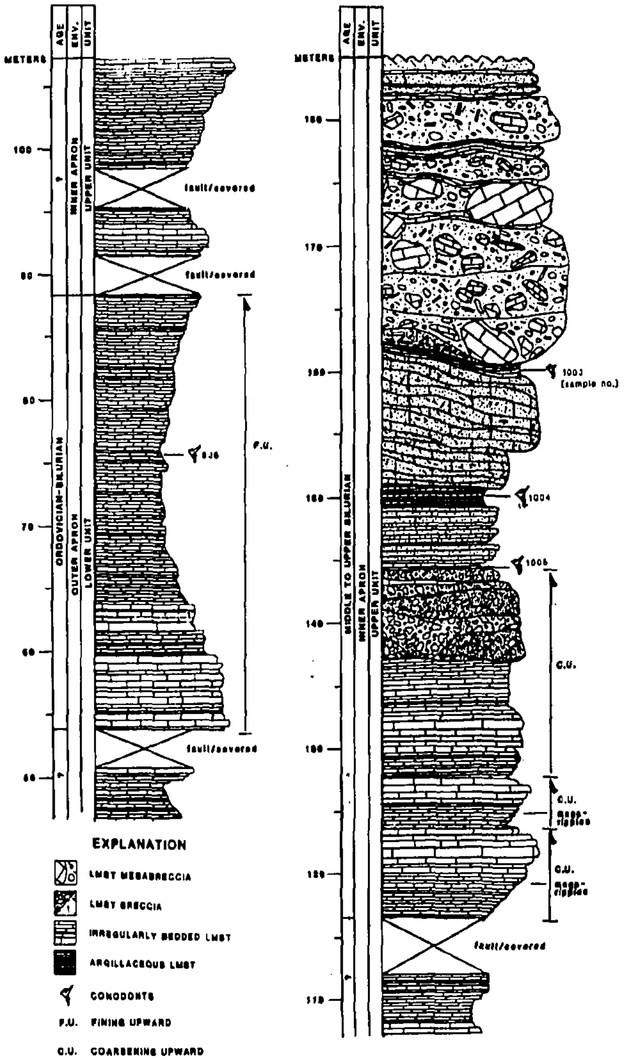

Figure 14. Limestone member diagram showing the upper unit, part of the lower unit, and conodont sample horizons.

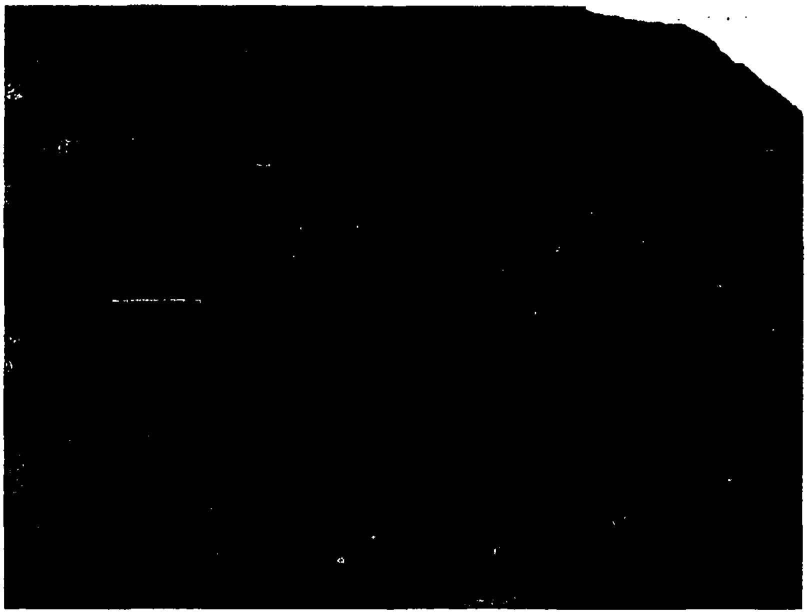

Figure 15. Outcrop of repetitively bedded limestone and argillaceous limestone from the lower unit of the limestone member.

bedding and upper-flow-regime planar laminations, T_a-T_b, make up a large portion of the lower unit (Facies C). However, the most common deposits are base-cut-out turbidites, T_b-T_e (Facies D). In the lower unit T_a and T_c are commonly missing or, possibly, indistinguishable because of recrystallization. One occurrence of matrix-supported, intraformational, carbonate conglomerate (Facies F) was found close to the base of this unit. It is composed of black, slabby clasts in a coarsely crystalline gray-black matrix.

Conodonts have been collected from one horizon in this unit (fig. 14).

3.4.2 Upper Unit

The upper unit of the limestone member is a sequence of thickly bedded limestone megabreccia, breccia, and coarsely crystalline limestone, interbedded with thinly bedded, laminated, argillaceous limestone. Several coarsening- and thickening-upward sequences occur in this section. Both matrix-supported breccia and conglomerate (fig. 16) and clast-supported, chaotic conglomerate (fig. 17) occur in this unit.

Lower in the upper unit of the limestone member, coarsely crystalline, graded beds of limestone form a thick (about 60 m) part of the section. Many of the beds have undulating tops

Figure 16. Debris flows in the limestone member. Note that this is a matrix supported conglomerate and that both rounded and angular clasts are present in this bed.

Figure 17. Edgewise conglomerate in the limestone member. Note that this lens shaped conglomerate is clast supported and that no rounded clasts are present.

(amplitudes of 10 to 12 cm and wavelengths of 0.6 to 1.5 m) and, flat bottoms giving the appearance of large ripples or megaripples. The beds exhibiting the megaripples are separated from each other by darker, finely crystalline, argillaceous limestone beds. Most have conformable bases, but beds with erosional bases do occur and fill broad erosional depressions. Internal laminations are common in both the coarsely crystalline limestone and the finely crystalline argillaceous limestones. Deformation has been ruled out as the origin of the undulatory bed forms because only the bed tops are undulating, while the internal features are unaffected. Thin, parallel laminations in the argillaceous limestone interbeds are undisturbed. The megaripple features are therefore taken to represent turbidity current deposition. This turbidite interval contains several coarsening- and thickening-upward sequences. Usually the intervals T_a and T_e (or sometimes T_d-T_e) are missing from individual turbidites depending on where they are located within these coarsening-upward sequences. This part of the section is part of Facies C.

Megaripples found at two locations in the upper unit indicate an approximate transport direction of N10^{o}E. Reliable paleocurrent indicators were not found at any other location in the Smith Formation, so there is insufficient data to define the overall basin configuration or directions of sediment transport.

The uppermost 24 m of the upper unit is composed predominately of megabreccia beds with thinner, silty limestone and calcareous shale interbeds (fig. 18). These fit the definition of megabreccia of Cook and others (1972) as a deposit in which angular clasts larger than 1 m across are conspicuous components and which may contain some clasts many meters across. Thick megabreccia beds contain clasts up to 4 m in diameter in an argillaceous limestone matrix. Although most clasts are recrystallized beyond recognition, two large (greater than 0.5 m) clasts have preserved grainstone fabrics. The thin, argillaceous limestone and calcareous shale interbeds are up to 2 m thick.

The megabreccia and breccia with muddy matrix and floating clasts were deposited as debris flows. Light-colored clasts that are rounded and spherical occur only in these upper unit debris flows in the limestone member. Their abraded appearance indicates long-distance transport and their light color indicates a source area outside the basin. A nearby shallow marine platform is the most reasonable source for these exotic clasts. Dark, platy, limestone clasts always occur with the rounded clasts, indicating that the debris flow had traveled a long distance, thus allowing the mixing of clasts from at least two different sources. Rounded clasts were mixed with intrabasinal clasts of platy limestone

Figure 18. Outcrop of the top 30 meters of the limestone member showing large clasts in debris flows.

prior to the deposition of the debris flows. These megabreccia and breccia beds are Facies F.

Black, platy, carbonate clasts are the major component of the clast-supported, chaotic conglomerates of the upper unit of the limestone member. These platy clasts are interpreted to be intrabasinal because they are unabraded and angular. The clasts are all identical in lithology and show no signs of mixing with muddy matrix material or exotic clasts. This evidence indicates that the clasts were transported only a short distance from a local source. The conglomerates probably were deposited as localized slides of semiconsolidated sediment and do not represent debris flows. These deposits are considered to be Facies F.

Fine-grained, thin-bedded, thinly laminated, lime mud occurs as thick accumulations (up to 2 m) of peri-platform ooze or hemipelagic sedimentation between some of the breccia and megabreccia beds. These laterally continuous beds are Facies G.

A large part of the upper unit is made up of grain-supported conglomerate beds which range from 10 cm to 1 m in thickness. The clasts are a combination of white to light brown and light gray, rounded limestone, and dark gray to black, platy limestone. These beds are relatively continuous and have thin argillaceous limestone interbeds. They are interpreted to be Facies A.

Conodonts were collected from three different horizons in the upper unit and other fossil collections have also been made by Dumoulin and Till (1985) from one of the same horizons.

3.4.3 Chronostratigraphy of the Limestone Member

In this study, conodonts were collected from four stratigraphic horizons of the limestone member (fig. 14) and identified by Timothy Carr, Atlantic Richfield Co. The upper unit of the limestone member has previously been dated by conodonts as middle Middle Silurian (Dumoulin and Till, 1985). No fossils have been collected from the lower unit during previous studies.

Sample number 836, collected from the lower member, yielded a single conodont. That conodont was poorly preserved and could only be identified as Ordovician through Devonian (Timothy Carr, written communication, 1985).

Three samples collected from peri-platform oozes of the upper member yielded 9 different species of conodonts (fig. 19) which have a maximum age of Middle Silurian (possibly early Wenlockian to very probable Ludlovian; fig. 20). This range is consistent with

	Polygnathoides siluricus Zone	Middle Silurian	Celloni–Amorphognathoides Zone
Genus and Species \ Collection Number	1003	1005	1004
Polygnathoides siluricus	X		
Ozarkodina inclinata	X		
sp.	X		
cf. hadra			X
Panderodus unicostatus	X		
sp.			X
Pseudo oneotodus	X		
Kockelella absidata	X		
cf. variabilis		X	
Carniodus sp.			X
Delotaxis sp.			X

Figure 19. Genus and species of conodonts from the limestone unit cross-referenced with collection and age data (written communication from T. Carr, Atlantic Richfield Co.)

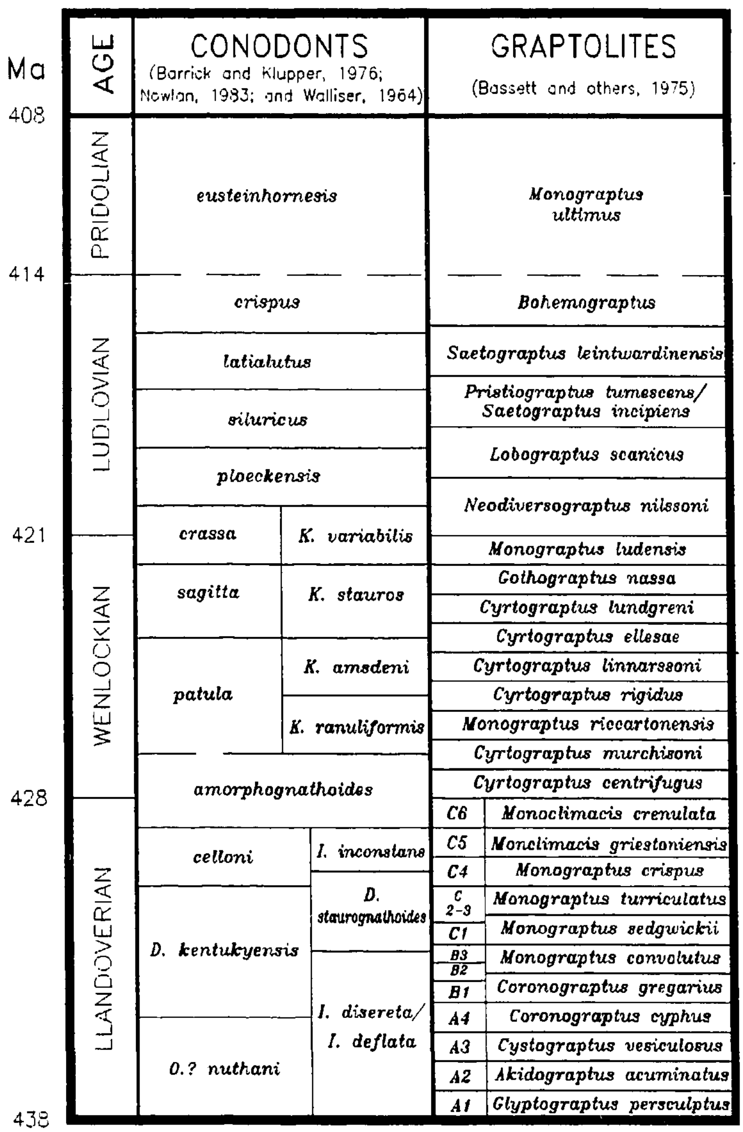

Figure 20. Biostratigraphic correlation chart for conodonts of the limestone member of the Smith Formation (written communication from T. Carr, Atlantic Richfield Co.).

the Wenlockian age determined by Anita G. Harris (cited in Dumoulin and Till, 1985).

Sample number 1003 is within the Siluricus Zone (415 to 419 Ma; absolute age correlations from Harland and others, 1983) and sample number 1004 is within the Celloni-Amorphognathoides Zone (426 to 430 Ma). The time span between the two samples is 7-15 Ma, and the thicknesses of the rocks between them is 10.7 m. The calculated sedimentation rate is 0.0007-0.00152 km/Ma (if no volume loss due to dissolution is assumed) is unusually low for slope or apron deposits (H.E. Cook, oral communication, 1985). Because the presence of turbidites and debris flows indicate deposition in high-energy, episodic events, the age data provides only a maximum age of deposition for this section.

The limestone member was probably deposited during Middle or Late Silurian time with the thick debris flow and interbedded peri-platform oozes at the top of the upper unit deposited no earlier than early Wenlockian. A major sea level fall occurred at the end of the Silurian Period [Sloss's (1963) Tippecanoe-Kaskaskia sequence boundary] and the limestone member is interpreted to represent shelf by-pass sedimentation during this sea-level low stand (Timothy Carr, written communication, 1985).

3.5 Dolostone and Limestone Member

3.5.1 Description

The dolostone and limestone member is exposed at Cape Deceit, 1.6 km northwest of Deering, Alaska (fig. 6). The section is at least 61 m thick, and the top and bottom of the section are covered. Most of the unit is severely recrystallized and faulted (fig. 21) so that original sedimentary structures are completely masked. Because of this recrystallization and faulting, the unit does not lend itself to detailed description. Unrecrystallized outcrop, where original sedimentary fabric is preserved, is limited to discontinuous exposures.

The existence of bedding in the dolostone and limestone member was never established. There are two explanations for this lack of internal stratification: (1) recrystallization and alteration has obliterated the original fabric selectively to obscure the bedding, or (2) the massive conglomerate and megabreccia beds are thicker than the outcrop.

The primary texture and internal features of the dolostone and limestone member are best preserved on the west side of Cape Deceit. Where primary fabrics are preserved, the unit is composed of light colored, yellow, brown and red dolostone and subordinate limestone conglomerate and megabreccia (fig. 22) which are clast-

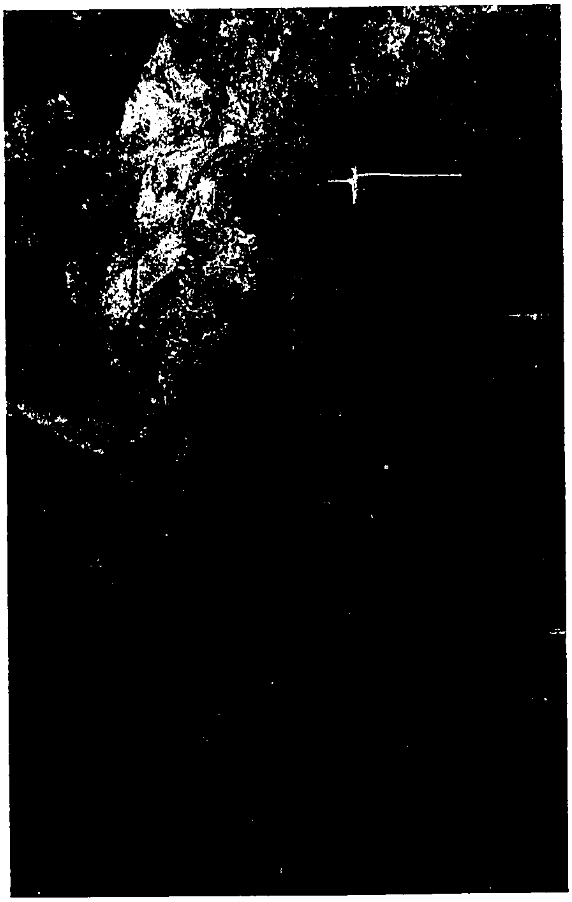

Figure 21. Outcrop of dolostone and limestone member. Note faulting and extensively altered nature of the outcrop.

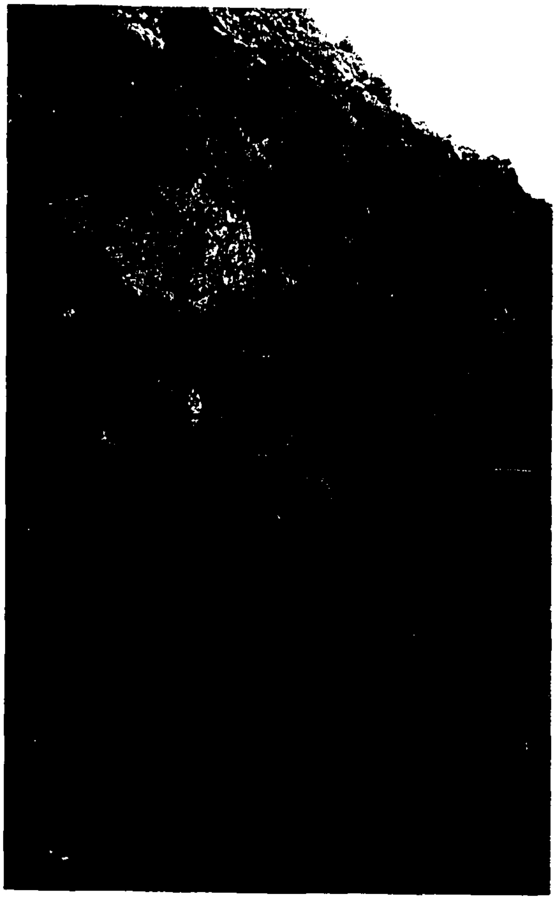

Figure 22. Outcrop of breccia in the dolostone and limestone member. Note that clast sizes and shapes vary significantly.

and matrix-supported. The matrix is dense, coarsely crystalline, mottled dolostone and limestone. Clasts are subangular to rounded and usually less than 25 cm in diameter, but range up to 1.25 m and thus fit the definition of megabreccia (Cook and others, 1972). The clasts within the dolostone and limestone member vary significantly in size, roundness and angularity along the outcrop but, due to the alteration of this section, it could not be determined whether these changes are abrupt or gradual.

Many of the clasts have the appearance of coral, shell (possibly gastropod and bivalve), or crinoid stem fragments, although recrystallization and dolomitization make identification impossible. For example, numerous circular clasts up to 1.5 cm in diameter having holes in their centers appear to be crinoid ossicles.

On the east side of Cape Deceit the dolostone and limestone member is highly faulted and fractured and has been extensively altered. Brecciation and alteration have produced extensive interconnected porosity, and iron staining is common. The rock is mostly porous, sucrosic, limestone and dolostone.

The variations in lithology of the dolostone and limestone member are due to both primary lithology and later alteration through dolomitization, recrystallization, faulting and alteration. However, there is enough primary fabric preserved to distinguish the original massive breccia character and other depositional features essential to understanding the relationship of the dolostone and limestone member to other less deformed rocks of the Smith Formation.

The dolostone and limestone member is predominantly muddy matrix-supported conglomerate and breccia with no evidence of grading or winnowing. The clasts in the dolostone and limestone member are relatively light in color in comparison to the matrix, indicating that the clasts may have originally formed in a different, possibly shallower and more oxygenated depositional environment. Therefore, the dolostone and limestone member is interpreted to be composed of massive carbonate debris flows of clasts derived from a shallow water source. The scale of the debris flows in this section cannot be determined, because no channels or stratification could be identified. However, one debris flow is certainly more than 20 m thick. These megabreccia and breccia represent Facies F deposition.

3.5.2 Chronostratigraphy of the Dolostone and Limestone Member

Kindle (1911) collected the only recorded megafossils from the rocks at Cape Deceit (section 1.4.2). This coral and lamellibranch bivalve collection has never been duplicated, although many workers have attempted to do so. (In this study only crinoid stem fragments, corals and shell fragments were found in these outcrops). For this reason, the validity of Kindle's collection remains uncertain. J.T. Dutro (cited in Till and others, 1986) considers the fauna described by Kindle to be of probable Silurian-Devonian age. A Silurian-Devonian age would indicate that this section may be correlative with, or younger than, the limestone member.

Dumoulin and Till (1985) collected a single conodont cone fragment from the dolostone and limestone member, which is Ordovician through Devonian in age. Samples collected for conodonts during this study were barren.

3.6 Other Well Preserved Sedimentary Rocks

Three other outcrops with preserved primary sedimentary fabric occur in the study area, but their stratigraphic and sedimentologic relationships to the Smith Formation are unknown. They are briefly described here for the sake of completeness. The outcrops are located at (1) Willow Bay, (2) three kilometers west of Cape Deceit, and (3) near Toawlevic Point (fig. 6).

3.6.1 Willow Bay

The outcrops at Willow Bay are a sequence of bedded (4 to 40 cm thick), coarsely crystalline marble and matrix-supported conglomerate in an apparently isolated fault block associated with a complex of calc- and mafic-schist. Primary sedimentary features include graded bedding and sole marks suggesting deposition as turbidites and debris flows. An abundant fauna of rugose and tabulate corals occurs as clasts in the thicker beds. Fossils collected from this unit were determined to be Devonian (probable Middle Devonian) in age (John Pandolfi, University of California-Davis, written communication, 1985). These rocks are younger than the Smith Formation.

3.6.2 West of Cape Deceit

The outcrop 3 km west of Cape Deceit is composed of thinly bedded, coarsely crystalline limestone and finely crystalline argillaceous limestone. The limestone beds have numerous flame structures and commonly contain euhedral pyrite crystals up to 0.5 cm. The interbeds of argillaceous limestone are bioturbated with trace fossils covering most surfaces. The thin beds of limestone were probably deposited as distal turbidites. The argillaceous interbeds were bioturbated during intervals of slow sedimentation between turbidite events.

The outcrop is small and contact relationships with the surrounding rocks could not be determined. No fossils were found in the outcrop and the age of the rocks is unknown.

3.6.3 Toawlevic Point

Bedded (4-25 cm thick), isoclinally folded limestone with subordinate limestone breccia occurs just west of Toawlevic Point. There are no age data from the outcrop and the relationship with the Smith Formation is not known.

3.7 Reconstructed Composite Section

When considered together, the three sections of well-preserved rocks of the Cape Deceit area represent a relatively complete stratigraphic succession. Therefore, these three sections were designated as the composite stratotype of the Smith Formation (Ryherd and Paris, 1987) (fig. 5).

The ages of the sections range from Late Ordovician to Late Silurian. Even though part of the shale and limestone member may have been deposited in the Lower Silurian, it still appears that there is some part of the section missing from the composite stratotype. This may be because deposition was temporarily interrupted during the Lower Silurian or because that part of the section is not exposed in the field area.

All the rocks of the Smith Formation were deposited as deep-water clastic sediments. No evidence of organic build-ups or reefs was found. The accumulation of thick sections of shale and megabreccia indicates the wide variation in the energy of the depositional medium common in the slope and basin margin setting. Within each member the variations were less pronounced.

The presence of deep-water carbonate rocks at Willow Bay, and similar well-preserved rocks at other locations in the area, indicates that carbonate slope and basin margin deposition occurred over a large part of the northern Seward Peninsula. Deposition probably continued into Devonian time as is indicated by the age of the rocks at Willow Bay.

The depositional environments of the composite section of the Smith Formation represent a prograding carbonate platform margin, from distal basin to proximal inner apron. The continued progradational succession represented by the three separate sections suggests that they are genetically related. The abundance of peri-platform oozes and other carbonate sediments in the shale and limestone member suggests that this slope carbonate sequence was close to a carbonate platform.

4.0 Depositional Model: Base-of-Slope Apron

4.1 Models for Deep-Water Carbonate Deposition

Deep-water facies and facies associations have been discussed by several authors. Interpretations in this study are based upon models presented by Mutti and Ricci Lucchi, 1972; Cook and others, 1972; Walker and Mutti, 1973; Walker, 1979, McIlreath and James, 1979; and Mullins and Cook, 1986.

In the late 1960's and early 1970's the first well-documented depositional models for basin margin carbonate and siliciclastic sediment gravity flow sequences were developed. Cook (1983) states that three of these depositional models are currently accepted for deep-water carbonate slope and basin margin deposits. They are:

1) submarine fan,
2) debris sheet,
3) debris apron,
    a) slope apron,
    b) base-of-slope apron.

Submarine fans are cone- or fan-shaped deposits that develop from point sources at the mouths of major submarine canyons (Bates and Jackson, 1980). Debris sheets are tabular bodies that originate parallel to and along platform margins (Cook and others, 1972). Debris aprons are wedge-shaped deposits which develop parallel to a carbonate shelf/slope break, in which sediments are shed down the slope as sheet-flows from a line source (Mullins and Cook, 1986). Walker (1966), Nelson and others (1970), Normark (1970), and Mutti and Ricci Lucchi (1972) developed the submarine-fan model at about the same time that Pray and others (1967) and Cook and others (1972) were establishing the carbonate debris sheet model. More recently, Mullins and Cook (1986) presented a debris apron model to better explain features of some deep-water sediments that do not fit the submarine-fan or debris-sheet models.

Today, the submarine-fan model and its variations is well established in the geologic literature and is widely used for paleoenvironmental interpretations of coarse-grained, deep-sea facies. Although this model has enjoyed success in its application to terrigenous, siliciclastic facies, it is apparent that the submarine-fan model can not be applied unequivocally to deep-water, carbonate, slope and basin margin deposits (Mullins and Cook, 1986). Fans are dominated by turbidity current processes with debris-flow deposits confined to their inner parts (Nelson and Nilsen, 1984). They are characterized by channelized flow along inner- and middle-fan regions and by sheet flow only on their outer portions (Nelson, 1983).

Debris sheets are characterized by breccia, conglomerate and sandstone that accumulate during nonchannelized sheet-flow events. Carbonate sheet-flow deposits are tabular-shaped beds, up to 20 m thick, with planar bases and irregular hummocky upper surfaces. They have clastic internal fabrics indicating deposition as debris flows and turbidites. Debris flows and turbidites are the dominant types of deposition found in the debris-sheet model. These deposits are not organized into identifiable facies sequences, as are other deep-water models. Instead, debris flows and turbidites are more randomly distributed. Also, debris-flow deposits form a major facies type in the debris-sheet model (Cook and Mullins, 1983). The numerous debris-flows represent major, episodic, collapse events along segments of a platform margin repeated throughout the depositional history (Mullins and Cook, 1986). Debris sheets are relatively rare but have been identified in the Devonian carbonates of western Canada (Cook and others, 1972; Cook and Mullins, 1983) and in the modern carbonate sediments of Exuma Sound, Bahamas (Crevello, 1978; Crevello and Schlager, 1980).

Mullins and Cook (1986) developed an apron model for deep-water carbonate sequences that does not fit the submarine-fan model of Mutti and Ricci Lucchi (1972). A comparison of the two models is shown in Figure 23. The carbonate apron model uses the same basic facies definitions of Mutti and Ricci Lucchi (1972), but the

FAN	FACIES ASSOCIATIONS (after Mutti and Ricchi Lucchi, 1972)	FACIES ASSOCIATIONS (after Mullins and Cook, 1986)	APRON
Slope	G dominates A and F are intercalated with G E fills channels D occurs between A units	G dominates A, C, or F fill numerous small canyons	Upper Slope
Inner Fan	Predominantly A, B, and F filling large channels cut into G units C, D, and E may occur as overbank deposits	F and A dominate as thick sheets F usually occurs only in this environment C may also occur	Inner Apron
Middle Fan	A, b and sometimes F fill large valleys cut into D units C and E may occur Positive megasequences are characteristic	A and D dominate as thick units F, if present, is rare and occurs as thin beds	Outer Apron
Outer Fan	C as large lenticular bodies D, E and F may occur Negative megasequences are characteristic		
Basin Plain	Alternations of D and G dominate C and F may be intercalated	Alternations of D and G dominate A and/or C punctuate deposition	Basin Plain

Figure 23. Association of turbidite facies and relative environments of deposition (after Mutti and Ricchi Lucchi, 1972; Mullins and Cook, 1986).

relationship between the facies are different. Debris-flow deposits are common in the apron model. Two types of carbonate aprons may develop. Along relatively gentle (<4°) platform-margin slopes, aprons form immediately adjacent to the shallow-water platform and are referred to as carbonate slope aprons. Along relatively steep (4-15°) platform-margin slopes, redeposited limestones accumulate in a base-of-slope setting, by-passing an upper slope via a multitude of small submarine canyons. The resulting deposits are referred to as carbonate base-of-slope aprons. In both apron models, even the most proximal sedimentation does not show significant channelization, and massive debris sheets can contain extremely large clasts. This is in contrast to the submarine-fan model in which sediments are deposited from point sources at the mouths of submarine canyons and proximal conglomerates and coarse sands fill large, erosive channels.

4.2 Environmental Interpretations

I interpret the individual members of the Smith Formation to have formed in a base-of-slope debris-apron environment. This interpretation is based on the presence of megabreccia in debris sheets as a major component, the relatively rare occurrence of channelization, and the overall coarsening- and thickening-upward character. However, the exact relationships between the isolated exposures is uncertain and specific lateral facies relationships cannot be determined from the single east-west cross-sectional exposure along the sea cliffs of Kotzebue Sound.

Environmental interpretations that follow, in stratigraphic order, range from the distal environments of the shale and limestone member through the relatively proximal environments of the limestone member and the dolostone and limestone member. The progradational character of the Smith Formation is easily apparent in this context. Thus, the Smith Formation is interpreted to represent progradation of an early Paleozoic carbonate apron.

4.2.1 Basin Plain Environment

The shale and limestone member is interpreted to have been deposited in a basin plain environment. Bedding is laterally continuous and plane-parallel. It is mostly made up of Facies D. Facies G sediments are volumetrically significant and Facies C is also present as a minor component at the base of the member.

The hemipelagic mud and turbidites of the graptolitic shale and limestone unit are the Facies D components of this environment. The thin, lenticular (non-channelized) character of some of the carbonate turbidites suggests that they are distal depositional lobes along an irregular apron front. Hemipelagic and pelagic mud and chert of the graptolitic shale unit, peri-platform ooze of the limestone unit, and hemipelagic mud and peri-platform ooze of the clay shale unit are Facies G sediments. The bedded limestone unit is interpreted as Facies C deposition. While Facies C deposits are not common in the basin plain, their presence may indicate the presence of large turbidite deposits in vast, flat deeps (Mutti and Ricci Lucchi, 1972).

The presence of the anomalous bedded limestone unit could be explained in at least two ways. The contact between the bedded limestone unit and the overlying graptolitic shale and limestone unit could represent a significant break in time, allowing for a change in depositional environment. Although the contact appears to be conformable little of it is exposed for inspection, and there is no age information on the bedded limestone unit to establish the relationship with the overlying unit. Alternatively, some unusual depositional event, such as the catastrophic collapse of a nearby shelf margin, may have been responsible for the presence of the bedded limestone unit in the basin plain environment.

4.2.2 Outer Apron

The lower unit of the limestone member was deposited in an outer apron environment. This unit is dominated by Facies C and D. Facies F occurs as a single occurrence near the base of the section. Turbidity current deposition is the only type of deposition found, with the exception of the Facies F just mentioned. No channelization is present in this part of the Smith Formation as is expected in the outer apron environment of the fan model. The total absence of megabreccia and channelization from this unit suggests that the environment of deposition is probably not inner apron.

4.2.3 Inner Apron

The upper unit of the limestone member was deposited in an inner apron environment. Clast-supported conglomerates and breccias, interpreted to be Facies A, are volumetrically the dominant lithology in the upper unit. Debris-flow deposits are next in importance to the clast-supported conglomerates and are interpreted to be Facies F. Carbonate turbidites in repeated coarsening- and thickening-upward sequences are Facies C. I interpret hemipelagic mud and peri-platform ooze intercalated with the debris flows to be facies G.

Clast-supported conglomerates (Facies A) and debris-flow and chaotic deposits (Facies F) were probably formed by collapse of nearby oversteepened slope material. The presence of a large percentage of Facies A and F deposits is essential to the interpretation of this unit as inner apron. Their presence indicates a close association with the source. Hemipelagic mud and peri-platform ooze (Facies G) punctuate the coarse sediments of Facies A and F and indicate that long periods of shelf-margin stability existed between episodic collapse events.

The dolostone and limestone member was deposited in an inner apron environment. It is composed only of debris flows (Facies F), with no lithologic breaks, shaly interbeds, or bedding of any kind. Mullins and Cook (1986) consider the presence of debris flows to be one of the diagnostic features of the inner apron environment. This member contains abundant relic fossils that appear unabraded. The presence of these relic fossils and the light colored matrix and clasts indicate that sediments were being introduced from the productive area of a carbonate platform with relatively little reworking.

4.3 Implied Platform Association

The presence of Ordovician through Silurian slope and basin facies with such high carbonate content indicates the presence of a nearby carbonate platform. Carbonate mud, in the volume that makes up the peri-platform oozes (Facies G) of the shale and limestone member and the limestone member, probably came from a carbonate platform source. True pelagic calcareous nanoplankton are first recognized from the Upper Silurian (Tucker, 1974). The shale and limestone member, however, was deposited during Ordovician time.

Because pelagic nanofossils (coccoliths and forams) were not present during the Ordovician Period, the only significant source of deep-marine lime mud in the shale and limestone member is a coeval carbonate platform (Scholle and others 1983).

The shelf in the study area during Ordovician through Silurian time may have been a distally steepened ramp (Read, 1985). This means that there was a large distance between regions of high organic production and the ramp edge. Shoal build-ups on the ramp would have been the major source of sediment reaching the ramp edge. This interpretation is supported by the presence of grainstone clasts and the absence of organic or skeletal material in debris flows.

By Devonian time the productive portion of the shelf had moved closer to the shelf edge. This made it easier for skeletal and organic debris to be incorporated in clasts swept off the shelf. This interpretation is supported by the high proportion of skeletal fragments in Devonian debris flows at nearby Willow Bay.

Because carbonate platforms are usually associated with passive margins far from centers of orogeny, the area around the central and northern Seward Peninsula was probably relatively tectonically stable during the time of Ordovician through Devonian carbonate deposition.

Using the interpretation that the Smith Formation was deposited as a progradational sequence near the edge of a platform, and that the platform was capable of providing a large supply of carbonate mud, a three-dimensional model was constructed. This model shows the relationships between the platform margin, slope, apron, and basin plain within a base-of-slope apron environment, and the position of debris flows and chaotic, clast-supported, collapse features at the base of the slope (fig. 24). In the model, basin plain sediments are composed of distal turbidites and pelagic, hemipelagic and peri-platform oozes. The upper apron is composed of breccia and megabreccia grading basinward into repetitively bedded turbidites interspersed with thick sections of carbonate mud or peri-platform ooze. The slope is largely peri-platform ooze cut by many small by-pass channels. The upper slope is extremely steep. In this model of sedimentation in the Smith Formation it is shown that the shelf margin actually may have become oversteepened and unstable. The rapid collapse of an over-steepened shelf margin would explain the massive conglomeratic character of the dolostone and limestone member highest in the reconstructed composite section. It is also possible that the shelf that supplied sediment for this apron system was largely

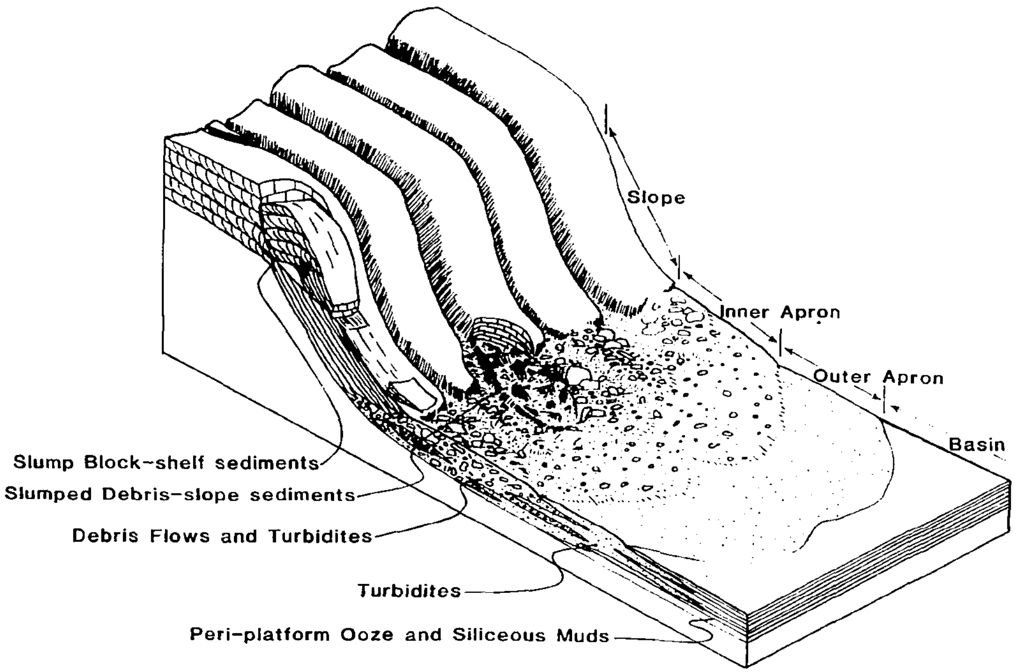

Figure 24. Reconstructed lower Paleozoic shelf margin, slope and base-of-slope apron showing sedimentation and depositional relationships.

composed of carbonate sand shoals (at least near the shelf edge), because of the noticeable lack of fossils and other recognizable organic material one would expect to find associated with shelf margin reef buildups.

5.0 Regional Relationships and Correlations

5.1 Metamorphic Petrology

Petrographic analysis was done to determine the metamorphic mineral assemblages and metamorphic facies of the rocks of the field area. The purpose was to aid in understanding the metamorphic history of the rocks in the study area and their relationship to the Nome Group of the central and southern Seward Peninsula. More than 100 thin-sections were prepared for this study.

Prior to investigation it seemed likely that either blueschist or greenschist facies mineral assemblages should be present in the rocks of the northern Seward Peninsula. This assumption was based upon work previously done on rocks from the area (Dumoulin and Till, 1985) and on correlation to similar Nome Group lithologies from the southern Seward Peninsula which have been shown to contain greenschist and blueschist facies minerals (Thurston, 1985).

5.1.1 Metamorphism and Metamorphic Rocks

5.1.1.1 Smith Formation

The well-preserved carbonates of the Smith Formation (and some other nearby locations) are almost pure marble, and relatively free of contamination from siliciclastic sediment sources. Shales do occur as a major part of the shale and limestone member, but metamorphism has resulted in only minor recrystallization and secondary mineral formation in these rocks. Therefore, diagnostic metamorphic minerals were not found in the Smith Formation. The best evidence of metamorphic activity in the Smith Formation is the pervasive recrystallization of the carbonate beds. The shales of the shale and limestone member have poorly developed slaty cleavage, but no significant metamorphic mineral formation is visible even with a petrographic microscope. There are no mineral assemblages that can be used to determine the metamorphic facies or pressure-temperature environment in any of the Smith Formation.

The CAI values (section 3.2) indicate that the Smith Formation underwent greenschist to amphibolite facies metamorphism. An additional indication of the possible metamorphic facies association is the position of the Smith Formation adjacent to the Nome Group which contains a greenschist facies metamorphic mineral assemblage. However, this assumes that the Smith Formation has always been closely associated with these more deformed rocks. Making such a definitive assumption is a tenuous step. The fact that the Smith Formation was never deformed also implies that it was heated in place—possibly at low (?) pressure (however, even a geothermal gradient of 30^{o}/km would require burial at a depth of at least 13 km). The absence of metamorphic minerals in the Smith Formation may indicate:

1. stress was not great enough during the regional metamorphic event that the Smith Formation was exposed to for the formation of new minerals and/or,
2. greenschist facies metamorphism did not occur and/or,
3. metamorphic minerals are too small to be recognized with a petrographic microscope and/or,
4. necessary constituents for the formation of metamorphic minerals were not present.

The first three items listed above seem to be rational explanations for the lack of metamorphic minerals in the Smith Formation. The lack of necessary constituents for the formation of metamorphic minerals seems less reasonable. It may be true for the relatively pure limestones and dolostones, but the shales present in this formation include a variety of constituents (calcite, clay, quartz, and feldspar) that could easily combine to form new minerals during normal regional metamorphism. I believe that the lack of identifiable metamorphic minerals is due to a combination of (1) a low-stress structural environment during metamorphism and (2) any metamorphic minerals that are present are too small to identify with a microscope.

5.1.1.2 Other Metamorphic Rocks

The metamorphic rocks of the adjacent intensely deformed rocks were examined to better understand their relationship with the Smith Formation. It seems reasonable that if a metamorphic grade was determined for the adjacent rocks, then the metamorphic grade of the Smith Formation could be implied by association, assuming that these rocks were closely associated during metamorphism.

Calc-silicate, calc-magnesian and siliceous metasedimentary rocks from outcrops adjacent to the Smith Formation, as well as east of Deering and at Toawlevic Point, contain metamorphic minerals which allow interpretation of metamorphic grade. The presence of chlorite + epidote ± quartz ± actinolite in calc-silicate and calc-magnesian rocks is described by Winkler (1979) as typical of greenschist facies. Since chlorite, epidote, actinolite and quartz are seen together in these rocks, they can be interpreted to have undergone greenschist facies regional metamorphism.

In Table 5 the common lithologies of the northern Seward Peninsula are shown correlated with the associated mineral assemblages. A.B. Till (U.S. Geological Survey, oral communication, 1987) suggests that the most prospective lithologies for finding diagnostic blueschist facies minerals on the northern

Table 5. Paragenesis of metamorphic rocks in the Deering area, indicating relative abundance of minerals identified.

LITHOLOGY	ABUNDANCE	MINERAL CONSTITUENTS
Marble	Abundant (>20%) Minor (<1%)	Calcite/dolomite Quartz, white mica, graphite
Calc-silicate Schist	Abundant (>20%) Common (10-20%) Subordinate (1-10%) Minor (<1%)	Calcite/dolomite Quartz, albite White mica, pyrite Graphite, sphene, hematite, epidote, chlorite, opaque sulphide
Calc-magnesian Schist	Abundant (>20%) Common (10-20%) Subordinate (1-10%) Minor (<1%)	Albite, clacite/dolomite Tremolite/actinolite Quartz, chlorite Apatite, whate mica, opaque sulphide
Siliceous Metasediment	Abundant (>20%) Common (10-20%) Subordinate (1-10%) Minor (<1%)	Quartz, feldspar White mica, calcite/dolomite Chlorite, pyrite Graphite, garnet, hematite, epidote, biotite, opaque sulphide, rutile
Mafic Schist	Abundant (>20%) Common (10-20%) Subordinate (1-10%) Minor (<1%)	Tremolite/actinolite Chlorite, calcite/dolomite Quartz, albite Garnet, opaque sulphide, hematite

Seward Peninsula are the mafic schists. Mafic schists located at Willow bay, approximately 15 km west of Deering, contain a large proportion of tremolite or actinolite and also lesser amounts of chlorite and calcite or dolomite. Unfortunately no diagnostic mineral assemblage is present.

The presence of low-temperature, high-pressure (blueschist) facies mineral assemblages is a widely discussed characteristic of the Nome Group. The presence of blueschist facies rocks is interesting because of the wide areal extent of its occurrence, and the lack of associated ophiolitic and subduction complex lithologies. It should be noted, in contrast to Thurston's (1985) findings that blueschist facies minerals are present in almost all lithologic units in southern Seward Peninsula rocks, that no blueschist facies minerals were found in the rocks of the study area.

The occurrence of blueschist facies minerals seems to decrease from south to north on the Seward Peninsula indicating a difference in metamorphic histories between the northern and southern Seward Peninsula. The northern-most occurrence of blueschist facies minerals is reported from mafic schists on the Inmachuk River southwest of the field area (A.B. Till, oral communication, 1987). Similar mafic schists are found in the field area and at other locations on the northern Seward Peninsula, but the blueschist facies minerals are not present.

5.2 Structural Geology

5.2.1 Analytical Methods

The northern Seward Peninsula is a structurally complex area, making the definition of structural elements an important aspect in interpreting the stratigraphy and determining the timing of major tectonic events that have affected the area. Any treatment of Paleozoic rocks in the Deering area requires understanding the complex structure.

Over 1000 structural measurements were made on coastal exposures in the field area. Every effort was made to obtain a representative data set when measuring structural features. However, due to the nature of most outcrops and the two-dimensional nature of most of the coastal exposures dealt with in this study, this goal may not have been achieved in all areas. Still, there are numerous measurements from widespread outcrops, so that representative megascopic structural features can be delineated from the data set. Analysis of structural data for this study was simplified through the use of FORTRAN based software developed by R. Koch (U.S. Geological Survey) for use on personal computers with an MS-DOS operating system.

Previous studies of the structural framework of the Seward Peninsula have concentrated on the western Seward Peninsula (Sainsbury, 1969b; Gardner and Hudson, 1984) and southern Seward Peninsula (Thurston, 1984; B.E. Patrick, unpublished manuscript). The structure of the northern Seward Peninsula is usually discussed in general terms by extrapolation of the structure and fabric trends from the south and west. Data presented here will increase the volume of structural information from this area.

5.2.2 Structural Elements

Fold axes and polar projections of foliation surfaces are plotted and contoured on lower hemisphere projections in Figures 25 and 26 respectively. Foliations (S_1) represent surfaces formed from the folding of primary sedimentary bedding (S_0). Folding occurs at microscopic, mesoscopic and macroscopic scales.

Shallow, eastward dipping foliation surfaces are the pervasive fabric element in the homogeneous calc-silicate schists seen at Deering Bluff and between Cape Deceit and Toawlevic Point. Thin (less than 4 cm thick) calcite veins in these rocks are isoclinally folded with amplitudes and wavelengths of less than 10 cm. Larger scale isoclinal folds with intense intrafolial folding are seen in

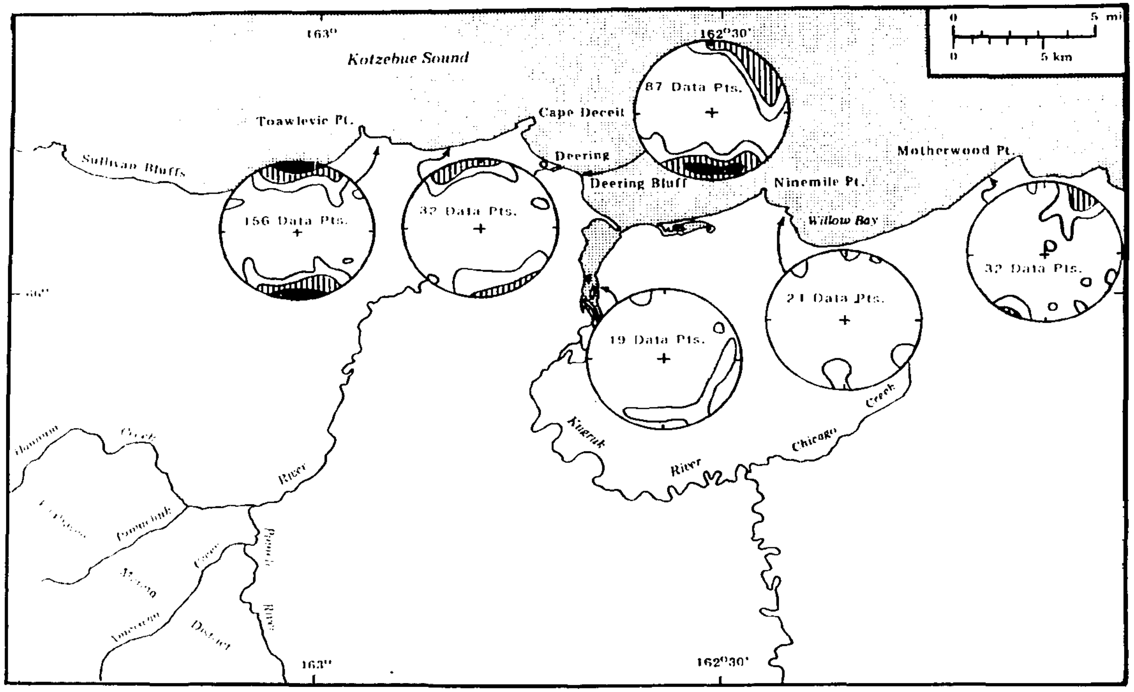

Figure 25. Location map and stereonets with fold axes contoured. Each stereonet location on the map indicates general area of original data.

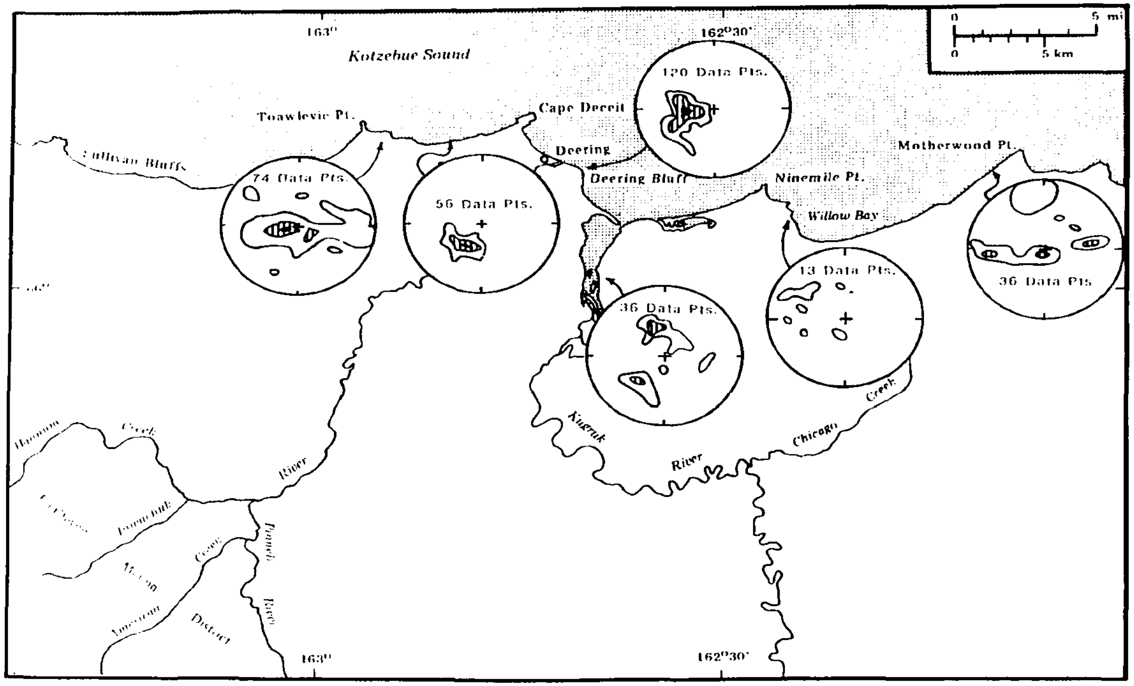

Figure 26. Location map and stereonets with poles of foliation surfaces contoured. Each stereonet location on the map indicates general area of original data.

the calc-silicate rocks between Cape Deceit and Toawlevic Point, but are not apparent at Deering Bluff.

Outcrops at Kugruk Lagoon, Willow Bay and Motherwood Point (figs. 25 and 26) contain a larger variety of lithologies and also have wider variations in the orientation of structural elements. Marble, calc-silicate schist and mafic schist are seen to be folded together and faulted, juxtaposing slivers of different lithologies. Isoclinal folds of mafic schist within calc-silicate schist are refolded at one location on Willow Bay. Foliations are found to parallel major lithologic boundaries in the field area.

5.2.3 Discussion

In general, fold axes in the Nome Group rocks adjacent to the Smith Formation plunge gently and suggest folding of the S_0 surface in macroscopic folds with fold axes similar in orientation to those of the mesoscopic fold axes (fig. 25). These structural elements have the same orientation as similar structures in the Nome Group of the Solomon quadrangle (B.E. Patrick, unpublished manuscript) and Teller quadrangles (Gardner and Hudson, 1984). This may indicate that structural elements of the Nome Group have some degree of homogeneity throughout the Seward Peninsula. Equivalent structures in the Nome Group have been correlated with a Late Jurassic metamorphic event, possibly as a consequence of a collision with the Yukon-Koyukuk island-arc (B.E. Patrick, unpublished manuscript).

Figures 6 and 7 show structural elements of the less deformed Smith Formation. The orientation of bedding is curiously similar to the orientation of foliation surfaces in the nearby deformed calc-silicate schist. A fault-bounded gabbro body is located between the two outcrops of the shale and limestone member (fig. 7). The gabbro body does not display the internal deformation seen in the calc-silicate schist of the surrounding metamorphic complex. However, pervasive alteration of olivines and feldspars is clear in thin-section, indicating some degree of metamorphism. Thus, while the age of the gabbro body is not known with certainty, it is probably at least older than the Late Jurassic metamorphic event.

The presence of the relatively undeformed Smith Formation in the intensely deformed and metamorphosed Seward terrane is difficult to explain. Outcrops of undeformed rocks making up the Smith Formation are unique with respect to the rocks of the central and northern Seward Peninsula (Dumoulin and Till, 1985). None of the contacts between the Smith Formation and the adjacent calc-silicate schist are visible. Significant differences in metamorphism and deformation suggest that they were separated at the time of metamorphism.

Possibly the two different rock types represent different structural levels in the same sedimentary pile. It is also possible that the more massive, Smith Formation did not deform as easily as other age correlative rocks [believed to have originally been mostly thin bedded deep-water carbonates (A.B. Till, oral communication, 1986)]. Their present positions at the same topographic level may reflect the formation of grabens which dropped structural blocks of less-deformed material down from a higher level, or macroscopic folding. The data available on the rocks of the field area do not support any further speculation on the presence of the Smith Formation within the intensely deformed Nome Group. The understanding of this relationship will have to await additional data, perhaps from geophysical studies, drilling, or mapping of a larger area.

5.3 Stratigraphic Correlations

The outcrops of the Smith Formation on the northern coast of the Seward Peninsula are located between the western Brooks range to the north and the central Seward Peninsula to the south. As such, they provide a link to aid in correlations between these areas, as discussed in this section.

5.3.1 Central and Northern Seward Peninsula

The relationship between the Smith Formation and rocks in adjacent regions is problematic because no rocks of equivalent lithology have been found on the Seward Peninsula. Modal mineral content of the calc-silicate and calc-magnesian schist in the study area indicates ratios of carbonate-quartz-mica that are quite different from those in any samples from the Smith Formation. Attempts to date the metamorphic rocks of the Solomon, Bendeleben and Kotzebue quadrangles have met with inconsistent results. Most outcrops have not yielded any fossils, so that age correlations between the schist and the Smith Formation remain uncertain.

Lower Paleozoic metasedimentary rocks of the Nome Group make up most of the central Seward Peninsula and some are interpreted to have been deposited in deep-water environments (Dumoulin and Till, 1985), similar to the environments interpreted for the Smith Formation. However, fossils found in these rocks are of different ages than those of the Smith Formation (Till and others, 1986). Thus, based on lithology, general age range, and environmental interpretations, it is probable that the Smith Formation is related to the Nome Group of the central Seward Peninsula, but no definitive statement can be made about this relationship.

5.3.2 York Mountains

The Smith Formation may be a deep-water equivalent of the platform carbonates of the York Mountains of the western Seward Peninsula. The Smith Formation is, at least in part, coeval with these rocks, and most of the rocks between Deering and western Seward Peninsula are lower Paleozoic Nome Group metacarbonates. Thus, the relationship between the carbonates of the York Mountains and the Smith Formation is similar to that between the rocks of the central Seward Peninsula and the Smith Formation, except that there is a greater distance between the Smith Formation and the York Mountains. In both cases there are correlations in age and lithology between the areas but, as expected, apparent differences in environments of deposition. Therefore, it seems likely that the York Mountain carbonates and the Smith Formation may have originally been part of the same carbonate platform. However, because of metamorphism, complex structure and lack of continuous exposure, no specific lithologic units can be traced between the rocks of the York Mountains and the Smith Formation leaving the lower Paleozoic depositional system of this region poorly defined.

5.3.3 Western Brooks Range

Correlations can be made between fossiliferous Devonian rocks from Willow Bay and rocks in the western Brooks Range. The fossiliferous breccias at Willow Bay are similar in faunal content, matrix and clast lithologies, color, and bedding character to a Silurian or Devonian (John Pandolfi, written communication, 1985) fossiliferous breccia collected in the Igichuk Hills (fig. 1) by an Atlantic Richfield Company field party (C.E. Paris, Atlantic Richfield Company, oral communication, 1985). The Igichuk Hills are located 210 km north of Deering in the western Brooks Range. The association of the rocks at Willow Bay with those of the Igichuk Hills and western Brooks Range is tenuous because of the great distance between the two regions, but it is interesting that these lithologic and chronologic equivalents occur on opposite sides of Kotzebue Sound. Based on the close association of the Smith Formation with the rocks of Willow Bay, a genetic relationship may exist between the Smith Formation and rocks of the Brooks Range.

Dumoulin and Harris (1987) present additional evidence supporting the Brooks Range-Seward Peninsula association. They have described Upper Silurian platform and shallow water dolostones near Angayukaqsraq (Hub) Mountain and on the central Squirrel River of the Baird Mountain quadrangle. These rocks are the same age as the limestone member of the Smith Formation. Also, Middle to Late Ordovician phyllite and metalimestone in the northeast Baird Mountain quadrangle are interpreted to be deep-water platform margin deposits and are age correlative with the shale and limestone member. Thus, there are carbonate platform and platform margin rocks of Silurian-Devonian age in the western Brooks Range similar to those in the study area. Lithologic and chronologic correlations do not constitute direct genetic correlations because of the structural complexities present in lower Paleozoic rocks of the region. However, correlation of age and lithology are strong evidence in favor of a common history when the proximity of the outcrops is considered.

5.3.4 Chukotsk Peninsula

The regional correlations between the Chukotsk Peninsula of eastern Siberia and the Seward Peninsula are certainly more tenuous than correlations with the York Mountains, but still quite interesting and deserve mention. Similarities have been suggested between Siberian tin granites and those on the Seward Peninsula (Miller, 1972), thus providing lithologic evidence that the two areas have been associated since, at least, Late Cretaceous time. Churkin and Trexler (1981) reproduce several stratigraphic sections from eastern Siberia which show that there are similar lower Paleozoic carbonate sequences in the Chukotsk Peninsula and the York Mountains of the Seward Peninsula. They also state that there is a genetic correlation between carbonate rocks of the Chukotsk Peninsula, the Seward Peninsula and the western Brooks Range. Obut and others' (1977) generalized Paleozoic stratigraphic column shows interesting age and lithology correlations between rocks of the Chukotsk and Seward Peninsulas. On the Chukotsk Peninsula, Upper Ordovician flaggy limestones and reef limestones containing evidence of abundant organic activity would correlate with Upper Ordovician peri-platform ooze of the Smith Formation. The Silurian System of the Chukotsk Peninsula comprises basinal graptolitic shales, carbonate breccias, and lenses of cross-laminated limestone. These sediments correlate with interbedded, Silurian limestone breccia and megabreccia, cross-laminated limestone, and argillaceous limestone of the Smith Formation.

5.4 Summary

Although the Smith Formation easily fits into the regional framework of the Seward Peninsula, it does not fit well with the local geology. While the metamorphic grade [as indicated by the CAI index (section 3.2)] of the Smith Formation is similar to that of the surrounding rocks, the style and degree of deformation are strikingly different. Also, the metamorphic grade of the Smith Formation is different than that of correlative rocks of the western Seward Peninsula and western Brooks Range, but the style and degree of deformation is analogous. This implies that the Smith Formation was not exposed to the same dynamic metamorphic event that caused the deformation of the surrounding rocks, but was faulted into place and underwent static burial metamorphism after the dynamic tectonic forces had subsided.

The Smith Formation does correlate in age and lithology with rocks in surrounding regions, but to date it has been impossible to trace units from one area to another. Depositional relationships between the northern Seward Peninsula and the western Brooks Range or the western Seward Peninsula will be difficult to define decisively.

6.0 Economic Potential

The basis for this detailed geologic study of the Smith Formation was ultimately economically motivated. The description of the rocks and interpretation of depositional environments are key elements in a thorough understanding of the economic potential of these rocks. The most likely types of minerals to be found associated with the Smith Formation are gold and stratiform Pb-Zn-Ag. The Smith Formation is believed to be of insignificant economic importance for petroleum resources.

6.1 Metallic Mineral Resource Potential

6.1.1 Placer Gold

Placer gold is currently being mined from stream gravel in the Fairhaven Mining District south of the field area (fig. 2). The total value of the gold produced from the Fairhaven Mining District was at least $10,000,000 through 1966 (Lu and others, 1968). Some mining is also being done in old stream channels buried by basalt flows in the same area. Mining has occurred from close to the mouth of the Inmachuk River to its headwaters. Most of the deposits lie above siliceous metasediments of the York slate (Sainsbury, 1974) and are not thought to be associated with marbles. Lithologically equivalent rocks crop out at Motherwood Point, east of the field area, and along the coast west of the field area. This indicates that the chances for an occurrence of placer gold along the coast in the field area are small, but there may be a slight possibility of a beach placer near Motherwood Point.

6.1.2 Lode Gold

The lode source(s) of the placer gold have not been clearly identified; there is one known minor occurrence. Hudson and DeYoung (1978) state that the lack of any identified large gold-bearing veins, combined with the known occurrence of gold-, silver-, and sulfide-bearing schist suggests, that principal lode gold deposits are of the disseminated type, as are the probable sources of gold on the southern Seward Peninsula. Lu and others (1968) and Sainsbury (1974) report the presence of a lode gold deposit on Hannum Creek (fig. 2) although the specifics of the deposit are not described in either study. It seems that there is little chance that lode gold would be associated with the Smith Formation.

6.1.3 Stratiform Pb-Zn-Ag Mineralization

A number of mineralized zones that trend northwest across Hannum and Harrys Creeks, southwest of the study area, have been shown by Herreid (1966) to have anomalously high assay values (10% lead, 2.2% zinc, and 60 g/t silver on Harrys Creek and 0.12% lead and 0.38% zinc on Hannum Creek). Mineralization, as disseminated sphalerite and less abundant galena, occurs within silicified schist zones, 100-200 m wide and over 1200 m long, in contact with marble (Hudson and DeYoung, 1978). The presence of this well-defined mineralization, as well as other gossans, indicates the likelihood of additional mineral deposits in the area. No silicified zones were observed in the field area. However, no detailed geochemical sampling was done during this study, so the occurrence of mineralization in the Smith Formation can not be ruled out. It seems more likely, however, that any mineralization that might be present in the field area would occur west of the Smith Formation exposures (possibly in the Toawlevic Point area) or east of Smith Formation exposures (possibly at Willow Bay). The rocks located in these areas are silicic metasediments and silicic metasediments host disseminated gold in the Fairhaven Mining District.

6.2 Petroleum Potential

Coastal exposures of the Smith Formation are located south of the Selawik and Hope Basins, both of which are virtually unexplored. Details of the source and reservoir potential of the Smith Formation are presented below followed by a brief description of the Selawik and Hope Basins.

6.2.1 Source Potential of the Smith Formation

The Smith Formation has poor potential as a hydrocarbon source. No organic geochemical analyses were done on samples from the study area to determine the type of organic material present. However, the thermal maturity of the Smith Formation is known, based on CAI values from conodonts. All CAI values from the Smith Formation are greater than 4.5 (400-700°C). This is too high for the survival of liquid hydrocarbons or commercial quantities of gas (Harris and others, 1987). Thus, even if organic material was of a type that might generate oil, it is overmature.

Prospective source rocks that were exposed to the Late Jurassic regional metamorphism would have heated beyond maturity. Thus, the Cretaceous-Tertiary sediments, which were deposited in a nonmarine depositional environment (section 1.5.2), would be the only likely hydrocarbon source candidates in the study area and in the sedimentary basins to the north. Source rocks from nonmarine sediments are commonly associated with gas generation, so there is a possibility that exploration would find more gas than oil in nearby basins.

6.2.2 Reservoir

The reservoir potential of the Smith Formation is difficult to assess because no systematic porosity or permeability studies were done in this study, and data from other sources have yielded mixed results. In general, coarse-grained, deep-water, carbonate sediment, gravity flow deposits are now recognized as important and attractive reservoirs for hydrocarbons (Cook and Enos, 1977; Scholle, 1977). Inner apron sediments are considered to be the principal exploration targets (Mullins and Cook, 1986). However, because the Smith Formation is thoroughly recrystallized, primary porosity has been effectively eliminated, even in the breccia units.

The dolostone and limestone member does show reservoir-quality porosity. Thin-section analysis of the dolostone and limestone member gave porosity estimates of up to 5-6%. The porosity is believed to be mostly interconnected and homogeneous over zones 20-100 m wide, associated with areas of extensive alteration and fracturing.

The reservoir potential of the Smith Formation is discounted because it is occurs unpredictably as small, erratic blocks within the structurally complex, less prospective Nome Group. These unfavorable characteristics may become less important to the north, but they probably still significantly reduce the possibilities of finding hydrocarbon reservoirs in this formation.

Reservoir potential assessment must include the consideration of a mechanism for the movement of hydrocarbons into the reservoir. This is problematic for the Smith Formation because of the poor source potential of the surrounding rocks. Possible scenarios for oil migration into a reservoir in the Smith Formation are limited to those where prospective Smith Formation reservoir rocks are juxtaposed with younger, more source-prospective, Cretaceous-Tertiary sediments. If the younger sediments overlie the Smith Formation, source rocks would have to be overpressured enough to force oil down into the prospective reservoir. Another favorable scenario would occur if the Smith Formation was part of a horst block within a basin of younger sediment, allowing hydrocarbons to migrate up into Smith Formation reservoirs.

The Smith Formation and correlative, relatively undeformed rocks may be present in the basement of the basins north of the field area. If this formation is present, porosity is abundant enough so that hydrocarbon reservoirs may occur within it. However, their occurrence will be difficult to determine using geophysical methods.

7.0 Conclusions

The Smith Formation is a well-preserved carbonate unit that occurs as fault blocks associated with intensely deformed metamorphic rocks. All known outcrops of the Smith Formation are in coastal exposures on the northern Seward Peninsula. CAI values from the Smith Formation indicate temperatures equivalent to greenschist facies metamorphism, but intense folding or ductile deformation did not occur. No evidence of blueschist facies minerals are present, indicating significant differences between metamorphic facies of the southern and northern Seward Peninsula. Thus, the Smith Formation is an anomaly on the northern Seward Peninsula, and provides important information or regional geology.

The Smith Formation contains numerous debris flows, turbidites, associated gravity flows, peri-platform ooze and hemipelagic shales. The sequence coarsens and thickens from bottom to top, and was deposited as a prograding base-of-slope apron. Environments recognized include basin plain, outer apron and inner apron.

Deposition occurred in deep-water, but closely associated with a productive shelf area. The lack of organic material or reef fragments in any of the clasts seen in the debris flows probably indicates that clasts did not originate directly from an organically productive zone. Organic activity occurred back on the shelf and any organic material that reached the shelf edge was reworked before it left the shelf. The distally steepened ramp model best fits these criteria.

Chronostratigraphic data and environmental interpretations of the shale and limestone member, the limestone member and the dolostone and limestone member of the Smith Formation indicate that deposition occurred during early Paleozoic time. Age and environmental relationships suggest that there is a genetic relationship between these three members, which occur as isolated outcrops in the study area. Stratigraphic sections from these outcrops have been reconstructed to form a composite section.

The Smith Formation contains fossils that permit correlation with other rocks in the region. Graptolites found in the shale and limestone member are Ordovician in age. Other graptolites in the region are found in the York Mountains of the western Seward Peninsula, in the western Brooks Range and on the Chukotsk Peninsula. Conodonts recovered in this study from the limestone member are Middle to Upper Silurian in age. These conodonts are the same age as conodonts from several other locations in the central Seward Peninsula.

Microscopic, mesoscopic, and macroscopic folds occur in the Nome Group on the northern Seward Peninsula, with most major fold axes trending roughly north-south. Isoclinal folding of calcite veins is common. Macroscopic regional folding is interpreted to exist, based upon interpretation of mesoscopic structural elements. This finding correlates with structures in the Nome Group of the Solomon and Teller quadrangles (section 5.2.3) indicating some degree of structural homogeneity over most of the Seward Peninsula.

There are no definitive explanations of the retention of original sedimentary fabric in the Smith Formation. It is possible that these rocks were faulted into position adjacent to the complex Nome Group. Fabric preservation in the Smith Formation may also be a function of the massiveness of bedding in parts of the formation.

The Smith Formation is correlative in age with carbonate rocks of the central Seward Peninsula, the York Mountains of the western Seward Peninsula, the Baird Mountains of the western Brooks Range, and with rocks of the Chukotsk Peninsula. However, in the central and western Seward Peninsula, and in most of the western Brooks Range, deposition occurred in shallow water while the Smith Formation was deposited in deep-water. The nearest occurrences of correlative deep-water carbonates are Ordovician through Silurian rocks on the Chukotsk Peninsula and at an isolated location near Hub Mountain in the western Brooks Range.

I believe the Smith Formation has little economic potential. The shales of the Smith Formation are overmature. The Smith Formation may be a reservoir for hydrocarbons, but only in areas where it is juxtaposed with viable source rocks. However, this would require a complex sequence of tectonic events and is therefore unlikely. The potential of the Smith Formation as a major host of economic gold deposits is insignificant. The largest economic potential of the Smith Formation appears to be its potential as a host for stratiform lead-zinc-silver deposits.

Appendix I

Deep-Water Sediment Facies Definitions

Table A-1 is a modification of Mutti and Ricci Lucchi's (1972) and Mullins and Cook's (1986) descriptions and definitions of the deep-water facies. The depositional facies from this table are the basis for interpretation of the depositional environment of the Smith Formation. Note that Facies B and E of Mutti and Ricci Lucchi (1972) are often rare or absent from carbonate aprons (Mullins and Cook, 1986).

Table I-1. Definition and description of deep-water sediment facies.

FACIES	DESCRIPTION (after Mutti and Ricci Lucchi, 1972 and Mullins and Cook, 1986)
Conglomerate and Breccia Facies A	Coarse-grained arenites and conglomerates; poorly sorted, and in thick to massive beds (greater than 1 to 2 m) which are irregularly shaped (due to channeling) and amalgamated. Muddy interbeds, if present, are very thin and have internal structures that include occasional grading and abundant mud clasts. This facies is inferred to be the product of highly erosive grain flow mechanisms.
Arenite Facies B	Medium-fine to coarse arenite; better sorted than the arenites of Facies A. Thick to massive lenticular beds are more laterally continuous than the arenites of Facies A. Thick, parallel or broadly undulating current laminae, often with mud clasts and erosional features are common. These sediments are inferred to be the product of both grain flows and high velocity turbidity currents (upper flow regime; particularly the anti-dune phase). Facies B is rarely present in carbonate aprons.
Arenite with Interbedded Mud Facies C	Medium- to fine-grained arenites (occasionally coarse-grained at the base of some beds) with minor amounts of homogeneous muds. The arenite beds are bounded by even and parallel surfaces with good lateral continuity. Small mud clasts either scattered or concentrated in distinct lenses and levels are common; broad, low-relief channels also may occur; and the complete Bouma sequence, Ba-e, may be present. These sediments are inferred to be the product of "classic" turbidity current deposits.
Mud with Interbedded Arenite (I) Facies D	Fine- and very fine-grained arenites, siltstones, and muds, having marked lateral continuity. Internal structures of the coarse-grained portions of these beds include thin current laminae which can be either parallel, undulating, convolute, or oblique (ripple drift). Although there are variations, the Bouma base-cut-out sequences of internal structures are invariably found. These sediments are inferred to be the product of dilute, low-density turbidity currents which deposited their sediment load primarily in the lower flow regime.
Mud with Interbedded Arenite (II) Facies E	Differentiated from Facies D by: (1) higher arenite-mud ratios, (2) thinner, irregular beds, (3) more discontinuous beds with wedging and lensing. Commonly the bed tops are in sharp contact with the overlying muds. Facies E is inferred to be the product of local processes (grain flows and turbidity currents) related to overbank depostion along more-or-less confined channels. Facies E is usually not present in carbonate aprons.
Chaotic Facies F	Mud-supported megabreccias, and mud-supported conglomerates formed from previously deposited sediments involved in slumps, mudflows, debris flows, grain flows and high-density turbidity currents. Sediments are characterized by heterogeneous, poorly sorted, disorganized, coarse-grained clasts in mud matrix. Megabreccias contain clasts with dimensions greater than 1 m and up to hundreds of meters in average diameter, and typically show no grading. Conglomerates and breccias differ in that most clasts in conglomerates have dimensions less than 10 cm and may exhibit crude normal or reverse grading.
Hemipelagic and Pelagic Facies G	Fine-grained sediments (peri-platform ooze, muds, shales, and marls) which are more-or-less silty and calcareous, with indistinct or poorly developed, parallel bedding. These sediments are inferred to be the product of various types of dilute suspensions including turbidity currents, nepheloid layers, etc.

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